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THE STRESS AND TEMPERATURE DEPENDENCE OF
CREEP IN AN AL-2.0WT%LI ALLOY

by

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The Stress and Temperature Dependence of Creep in an Al-2.0wt%Li Alloy

by

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ABSTRACT

The effect of stress and temperature on the creep behavior of an Al-2.0wt%.Li alloy was investigated in the temperature range from 300 to 500°C. This temperature interval corresponds to a solid solution of Li in Al. Experimental results indicate that Al-2.0wt%Li behaves as a pure metal class alloy (class II). This is demonstrated by several creep characteristics including the value of the stress exponent (n ~ 5), the shape of the creep curve, and the nature of the creep transient after a temperature change. However, anomalous behavior of the activation energy was observed. Activation energies up to 55 kcal/mole, decreasing to approximately 33 kcal/mole at higher temperatures, were observed by the temperature cycling technique.

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I. INTRODUCTION

Both the blacksmiths of old and today's metallurgists have long recognized that small changes to processing variables or to alloy compositions can create widely varying effects on the mechanical properties of the resulting metal. Metallurgists today attribute these effects on the mechanical properties to changes in the microstructure. Now, metallurgists must explore and exploit these effects to meet the demands of today's rapidly evolving materials needs.

From Italy's Da Vinci to America's Wright brothers, aviation has always been at the forefront of technology. Military specifications dictate that putting more payload in the air is the overwhelming factor in design. Aluminum alloys are the predominant materials of airframe construction because of their high strength-to-weight ratio when used as beam structures and aircraft skin. Criteria used to evaluate metals for aerospace applications begin with relative strength and density. However, some components must withstand necessarily high temperatures as well as maintain good strength characteristics. Other important criteria include resistance to cyclic fatigue, corrosion resistance, weldability and good appearance.

Many materials have adequately met these criteria and are in wide use today. Factors which spur continued research in high strength, temperature resistant Aluminum alloys are cost of materials, as well as fabrication and lifecycle costs. When Li is added to Al it forms an alloy with a lower density and a higher modulus of elasticity than pure Al. Yet Al-Li alloys without other alloying elements are not widely used commercially due to poor mechanical properties. When other alloying elements are added to Al-Li systems, the mechanical

properties can be improved dramatically. At ambient temperatures, the mechanical properties of Al-Li alloys are well known. These include factors such as high strength-to-weight and stiffness-to-weight ratios, and good toughness and cyclic fatigue characteristics. However, very little information exists on the high temperature behavior of the Al-Li system. Thus, limits on elevated temperature exposure of these alloys have yet to be determined. Therefore, it is the main thrust of this investigation to expand the body of data on an Al-2.0wt%Li alloy in terms of the stress and temperature dependence of its creep behavior, as well as to investigate the activation energies for creep in the temperature range 300 to 500^{o}C.

II. BACKGROUND

A. CREEP OF SOLID-SOLUTION ALLOYS

This research considered the constant stress creep behavior of Al-2.0wt%Li in the temperature range from 300 to 500°C. The solvus temperature for this alloy is ~ 360°C (see Figure 1).Thus at 300 and 350°C effects may arise due to precipitation. From 400°C upwards, the effects of solid solution strengthening alone, without influence from precipitation , will be observed.

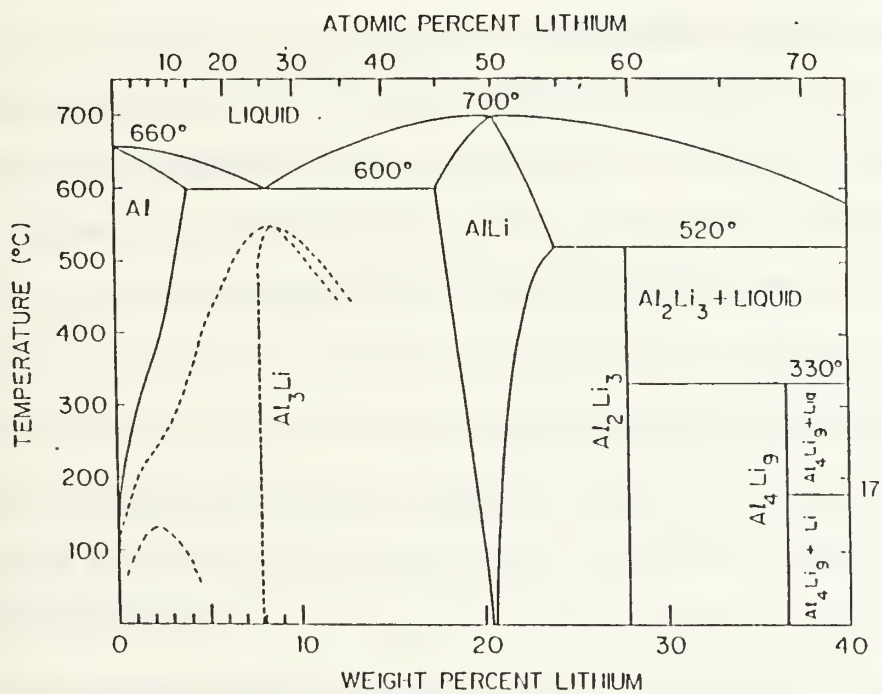

Figure 1. Al-Li Phase Diagram

The creep response of solid solutions has been classified into two categories based on the premise that dislocation motion occurs through sequential glide and climb processes [Ref. 1].

1. Class I Solid Solutions

The first category commonly referred to as class I or alloy class, exhibits dislocation glide as the rate-controlling process during deformation due to solute drag on the moving dislocations. Class I alloys commonly exhibit a stress exponent, n ($= d \ln \sigma / d \ln \dot{\varepsilon}$), of about 3, a brief primary stage of creep and random distribution of dislocations. The activation energy is equal to that for solute diffusion.

2. Class II Solid Solutions

The second category is called class II or pure metal class, where dislocation climb becomes rate-controlling. Class II alloys exhibit a stress exponent, n, close to 5, extensive primary creep and subgrain formation. The activation energy is essentially equal to that for self-diffusion.

B. STRUCTURE OF AL-LI ALLOYS

1. Effect of Li Addition in Al

As an addition to Al alloys, Li offers a significant decrease in density and increase in modulus of elasticity. Li has a high solubility in Al (5.2%) in the binary Al-Li system. Greatly improved strengths result from the δ' (Al_3Li phase) precipitation during age hardening. Also, each percent of Li added to Al reduces the density of the alloy by 3% and increases the modulus of elasticity by 6%, up to 4 % Li additions.

The role of Li increasing the modulus of elasticity of Al has been addressed recently in a paper by Fox and Fisher on a study of 1.33 and 2.14wt%

Lithium additions to Al. The Li addition in Al results in an increase in the electron charge density between Al and Li atoms. Accordingly, this increase in charge density results in an increased average force of attraction between the atoms and thus an increased modulus of elasticity.[Ref. 2]

2. Ordering in the Al-Li Matrix

Radmilovic, Fox and Thomas contend that ordering exists within the range of the solid solution and not only in the temperature region below the solvus. This was based on the observation of superlattice reflections and no discernable δ' particles irrespective of prior solution treatment temperature or quench medium employed following solution treatment. The ordered alloy apparently decomposes into a modulated order/disorder structure by a spinodal mechanism with increased Li content in the ordered regions until such regions coarsened into discrete δ' particles.[Ref. 3]

The increased modulus and the presence of ordering in the solid solution are evidence that Al and Li atoms tend to bond readily. The temperature dependence of such bonding has not been addressed. It has been shown, however, that both the modulus of elasticity and the stacking fault energy influence the creep behavior of materials, hence it is likely that the creep response of Al-Li alloys may be influenced by Li addition through these material parameters [Ref. 1].

C. THE MECHANISM OF CREEP

1. Interaction of Dislocations and Solute Atoms

A dislocation has a stress field associated with it. Solute atoms, because their sizes are either too small or too large in relation to the solvent atom size, are also centers of elastic strain. Consequently, the stress fields from these

sources can interact and can mutually exert force. This is an elastic interaction due to misfit.

The interaction of the solute atoms and edge dislocations leads to a migration of solute atoms to the dislocation where they form an atmosphere around it. This solute atmosphere, called the Cottrell atmosphere, has the effect of locking the dislocation. This makes it necessary to apply additional force to free the dislocation from the atmosphere.[Ref. 4]

Li atoms are very close to the same size as Al atoms. However, even when the size difference is zero, a contribution to the binding energy between the solute and the dislocation can result due to the difference in modulus between the two. The solute atom behaves as an elastic heterogeneity in the dislocation strain field. If the solute is softer (i.e. smaller shear modulus) than the matrix, the energy of the strain field of the dislocation can be reduced by distortion of solute. This means that the energy will be negative and thus there will be an attraction between the solute and the matrix. For a solute that is harder than the matrix, there will be a force of repulsion between the two.[Ref. 4]

At high temperatures (> 0.5 Tm), the mobility of the solute atoms will be much greater than that of the dislocation, with the result that they will not restrict the dislocation motion. In the range of temperature where solute atoms and dislocations are equally mobile, there are strong interactions with dislocations.[Ref. 4]

The movement of dislocations will result in disordering of ordered regions in a partially ordered alloy. This disruption would cause an increase in the energy of the material and requires additional work to be done. Mechanical properties thus are altered when materials have an ordered structure. Fully

ordered alloys may deform by means of the movement of superlattice dislocations at rather low stresses. However, the super dislocations (i.e. closely spaced pairs of unit dislocations bound together by an antiphase boundary) must move as pairs in order to maintain the ordered structure. This makes cross-slip and climb more difficult. Long-range order thus leads to high rates of strain-hardening and frequently to brittle fracture as well as high-temperature creep resistance.[Ref. 4]

2. Creep Rate Dependence on Temperature

Creep is a thermally activated process. Thus, the creep rate, $\dot{\varepsilon}_{min}$, can be described by an Arrhenius type of relation:

$$\dot{\varepsilon}_{min} \ \alpha \ \exp\left(\frac{-Qc}{RT} \right) \tag{1}$$

where Qc is the activation energy for creep, R is the gas constant, and T is the absolute temperature. This has been demonstrated by several experiments.[e.g. Ref. 1]

3. Creep Rate Dependence on Diffusion

If the creep rate is dependent on dislocation climb or upon the motion of jogged screw dislocations, then the steady state creep rate, $\dot{\varepsilon}_{min}$, should be proportional to an appropriate diffusion coefficient, D:

$$\dot{\varepsilon}_{min} \ \alpha \ D \tag{2}$$

and there is ample evidence for the correlation of $\dot{\varepsilon}_{min}$ and D. For example, the steady-state creep rate stress data at various temperatures for a given metal can be made to virtually coincide if the creep rate is first divided by the diffusion coefficient for the appropriate temperature and then plotted against stress. Since the creep rate is proportional to the diffusion coefficient, it is logical that the

activation energy for creep of pure metals should be about equal the activation energy for self diffusion.[Ref. 1]

4. Creep Rate Dependence on Stress

Sherby and Burke [Ref. 1] note that for low and intermediate stresses, the relationship between the creep strain rate and stress (at constant temperature) can be described by the power-law relation:

$$\dot{\varepsilon}_{min} \; \alpha \; \sigma^n \tag{3}$$

where σ is the stress. If creep can occur by several different independent processes, the fastest of these will be rate-controlling. Thus, the mechanism of creep at very low stresses (range I) can be associated with the creep law:

$$\dot{\varepsilon}_{min} \; \alpha \; \sigma^1 \tag{4}$$

where n equals 1, since this creep process yields a more rapid creep rate than the process responsible for the intermediate stress (range II) where:

$$\dot{\varepsilon}_{min} \; \alpha \; \sigma^n \tag{5}$$

and where the value of the stress exponent, n, is greater than 1 [Ref 1]. With increasing stress, it is expected that a transition in creep mechanisms will occur as the rate of range II processes increases more rapidily with stress than the rate of range I processes.

5. Class I Alloys and Their Creep Rate

Sherby and Burke [Ref. 1: p. 341] note that creep of solid solution alloys between $\dot{\varepsilon}/D$ values ranging typically from 10^2 to 10^9 cm^{-2} can be divided into two categories. Class I alloys are first and their strain rate is proportional to the cube of the modulus-normalized stress:

$$\dot{\varepsilon}_{min} = B\, D_S \left(\frac{\sigma}{E}\right)^3 \tag{6}$$

where $\dot{\varepsilon}_{min}$ is the strain rate, B is a physical constant, D_s is the diffusion coefficient for the solute, σ is the true stress, E is the elastic modulus and n is equal to three. Dislocation glide is the mechanism for creep where the velocity of the dislocation motion is determined by the amount of friction that the solute atoms generate to oppose the glide motion. The activation energy for creep would be the activation energy for diffusion of the Li solute.

6. Class II Alloys and Their Creep Rate

Class II alloys are the second classification and their strain rate, $\dot{\varepsilon}_{min}$, is proportional to the cube of the stacking fault energy, $(\gamma)^3$, to the modulus-normalized stress raised to the fifth power, $(\frac{\sigma}{E})^5$ and to the self-diffusion coefficient, D_l:

$$\dot{\varepsilon}_{min} = A\,(\gamma)^3\,(\frac{\sigma}{E})^5\,D_l \tag{7}$$

where A is a material constant, R is the gas constant, and n is equal to five. The mechanism of creep in this class is dislocation climb, the rate of which is also affected by subgrain size. Class II alloys exhibit a distinct primary creep stage, similar to pure metals, and the activation energy for creep can be anticipated to be the same as the activation energy for self-diffusion. On the basis of increased modulus alone, one could anticipate that the strain rate of the alloy would be slower than that of Al for either class I or class II alloys.

D. OTHER EFFECTS ON THE ACTIVATION ENERGY

The activation energy for a given metal can be calculated if the creep rate is known at two temperatures:

$$Q_c = -R\,\left(\frac{\Delta \log \dot{\varepsilon}}{\Delta \frac{1}{T}}\right)\Big|_{\sigma,\varepsilon} \tag{8}$$

Earlier, it was noted that the activation energy for creep was about equal to the activation energy for self-diffusion. If, however, the modulus were to be strongly temperature dependent, the activation energy for creep would not be exactly equal to the activation energy for self-diffusion. Similarily, the stacking fault energy may vary with temperature. The influence of such temperature dependent factors can be shown with the aid of equations 7 and 8:

$$Q_c = -R \left(\frac{\Delta \log \dot{\varepsilon}}{\Delta \frac{1}{T}} \right) \Big|_{\sigma,\varepsilon} = -R \frac{\partial \ln D}{\partial \frac{1}{T}} \Big|_{\sigma,\varepsilon} + 5R \frac{\partial \ln E}{\partial \frac{1}{T}} \Big|_{\sigma,\varepsilon} - 3R \frac{\partial \ln \gamma}{\partial \frac{1}{T}} \Big|_{\sigma,\varepsilon} \quad (9)$$

The term $-R\, \partial \ln D / \partial(1/T)$ is simply equal to the activation energy for self-diffusion. So, equation 9 becomes:

$$Q_c = Q_d + 5R \frac{\partial \ln E}{\partial \frac{1}{T}} - 3R \frac{\partial \ln \gamma}{\partial \frac{1}{T}} \quad (10).$$

If E and γ do not change much with temperature, then Q_c will effectively equal Q_d. However, if E and γ are strongly temperature dependent then Q_c would differ from Q_d.

This, in fact was found to be the case, as experimentally determined values of Q_c were observed to be greater than known values of Q_d for pure Al in the temperature range of 300 to 470°C.

E. PREVIOUS RESEARCH AT NPS

Anomously high activation energies were reported by Taylor [Ref. 5] in his study of Al-0.5wt%Li and Al-1.0wt%Li, as well as by Ellison [Ref. 6] in his study of Al-2.0wt%Li. These results were attributed to the alloy's temperature dependence of the modulus and the stacking fault energy relative to pure Al. These results represent the initial point where this study of the creep behavior and of the activation energy for Al-2.0wt%Li commences.

III. EXPERIMENTAL PROCEDURE

A. CASTING AND SECTIONING

A Al-2.0wt%Li casting, number NPGS13 and manufactured utilizing 99.99 percent pure Aluminum alloyed with 99.90 percent pure Lithium, was received from the Naval Surface Weapons Center (NSWC) in White Oak, Maryland. The casting was in the form of a tapered cylindrical ingot 200 mm (8.0 in) in length and approximately 76 mm (3.0 in) in diameter.The casting was sectioned into billets for subsequent solution treatment and processing. The traverse sections were 25 mm (1.0 in) thick and 76 mm (3.0 in) in diameter.

B. THERMOMECHANICAL PROCESSING

Solution treatment was conducted at 540^{o}C for 12 hours with a subsequent water quench to room temperature. A Lindburg Type B-6 heavy duty furnace was used for homogenization. For rolling, the homogenized billet was placed in a Blue M furnace, Model 8655f-3, for 5 minutes reheating at temperatures between 400^{o}C and 450^{o}C prior to each rolling pass. A massive steel plate was located on the floor of the furnace to act as a heat capacitor in order to maintain a stable annealing temperature. Care was taken to commence the 5 minute anneal "clock" once the temperature of the billet was above 400^{o}C.The last rolling pass was followed by cold water quenching to room temperature. The TMP is schematically represented in Figure 2.

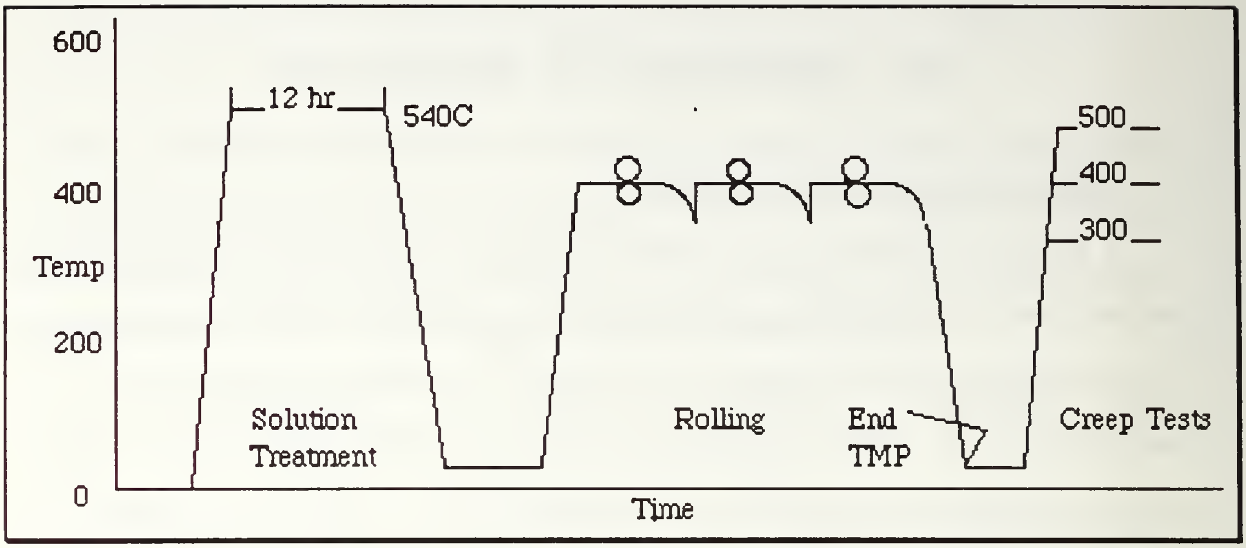

Figure 2. TMP for Samples

Billets were rolled in a Fenn Laboratory Rolling Mill using the reduction scheme shown in Table 1. By turning the screw down wheels the number of turns indicated (second column) to the setting shown (third column), then the mill gap indicated (fourth column) would result in the amount of strain per pass shown (last column).

The resulting rolled strip, nominally 2 mm (0.08 in) in thickness, was machined to dimensions for tensile testing, see Figure 3. The rolled strip was first cut by band saw into rectangular blanks and machined into reduced gauge section, sheet-type, tensile specimens with the long axis parallel to the rolling direction. A special holding device was fabricated to secure the samples duiing machining due to the extreme softness and ductility of the material. Five specimens were machined at one time. The finished samples were examined for defects and all machining burrs were carefully removed with a jeweler's file.

Prior to testing, all samples received a heat treatment of 15 minutes at 500°C to provide a fully annealed microstructure.

Table 1. ROLLING SCHEDULE

ROLL #	ROLL CHANGE (0.08 in + 0.01 in)	MILL SETTING (right/left)	MILL GAP (in)	% STRAIN (per pass)
open	+(12 + 4)	0/0	0.94	--
1	-(2 + 0)	0/0	0.84	10.4
2	-(1 + 2)	6/6	0.74	12.0
3	-(1 + 2)	4/4	0.64	13.5
4	-(1 + 2)	2/2	0.54	15.6
5	-(1 + 2)	0/0	0.44	18.5
6	-(1 + 2)	6/6	0.34	22.7
7	-(1 + 2)	4/4	0.24	29.4
8	-(0 + 6)	6/6	0.18	25.0
9	-(0 + 5)	1/1	0.13	27.7
10	-(0 + 4)	5/5	0.09	30.7
11	-(0 + 3)	2/2	0.06	33.3
12	-(0 + 1.3)	0.7/0.7	0.047	21.7

C CONSTANT EXTENSION RATE TESTS

Constant extension rate tensile tests were performed on an Instron TM-S-L Table Model Universal Testing Machine with a 1,000-pound calibrated load cell.

The tensile testing temperature was maintained by a Marshall tubular furnace in combination with a Lindburg Model 59344 temperature controller.

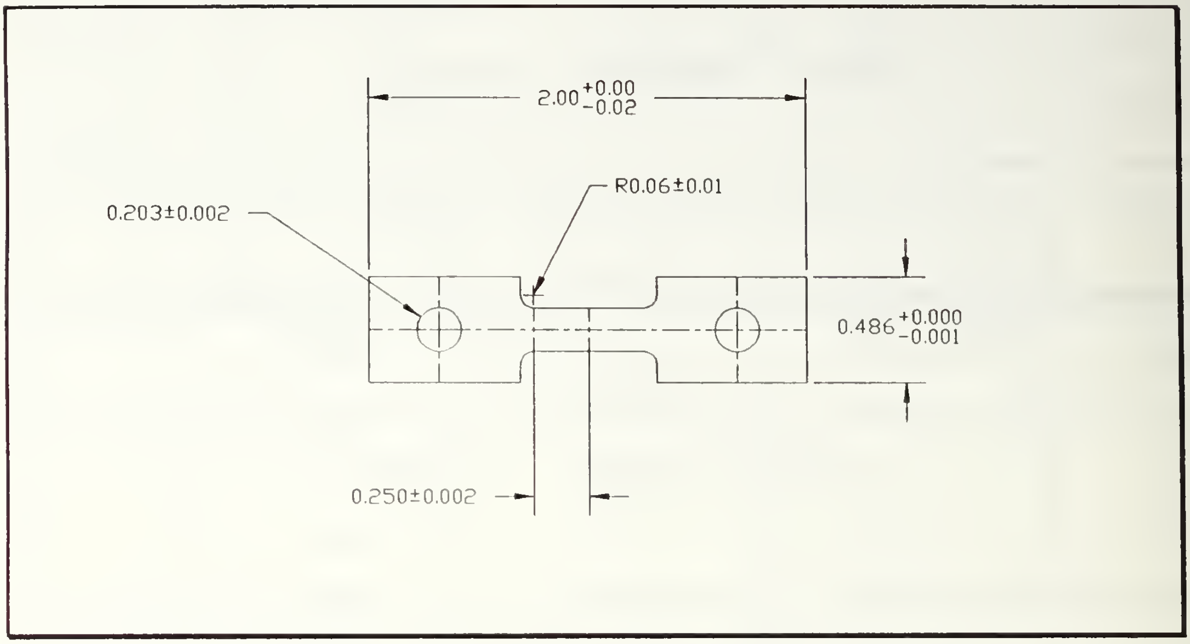

Figure 3. Tensile Test Specimen Drawing

Special self-aligning grips were designed to hold the tensile test specimens (Figure 4)[Ref. 5]. These grips were fabricated of Inconel 625 alloy by Collins Instrument Company, Freeport, Texas, using a wire electro-discharge machining (EMD) process for tolerance control.

Unique features of these grips include a tapered shank leading to a button head which aligns itself by transmitting the load to the grips via the taper. The recessed face of the grips compressively hold the specimen, applying the load to the entire tab, not just the area above the bolt hole.

Once temperature was attained, the furnace was de-energized, lowered, and the grip assembly with the sample installed was inserted into the grip holder

assembly. The furnace was raised, re-energized and allowed again to stabilize for approximately 45 minutes. While the sample and grips were equilibrating, the slack was removed from the load train by a small pre-load in order to prevent slippage in the grips. Since the entire gauge/grip/heater assembly is mounted to the bottom of the crosshead and moves down with the crosshead as the test progresses, the original temperature gradient can be maintained for any extension likely to be encountered with this alloy.

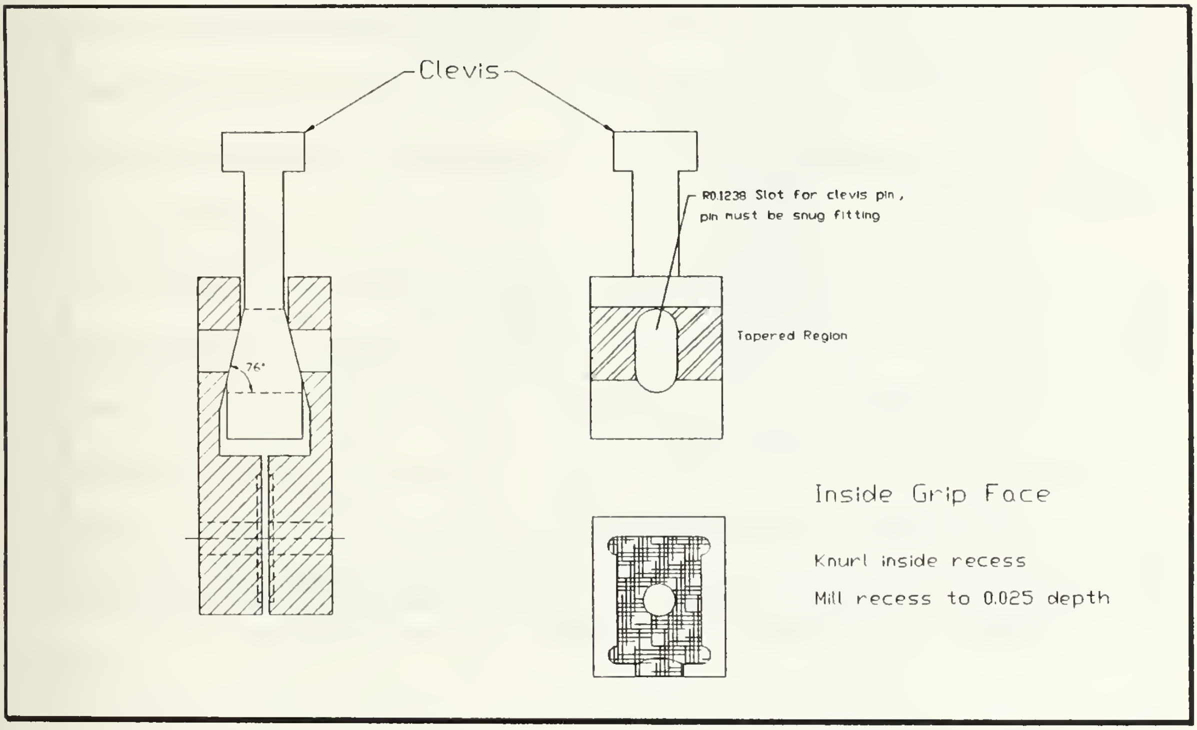

Figure 4. Self-Aligning Grip Assembly

D CONSTANT STRESS TESTS

Constant stress tensile creep tests were conducted on a pair of test machines designed at NPS and were patterned after a machine built by Barrett and later

modified by Matlock at Stanford University [Ref 6]. The constant stress is obtained by means of an Andradre-Chalmers lever arm. The contoured lever rotates as the specimen elongates (Figure 5).

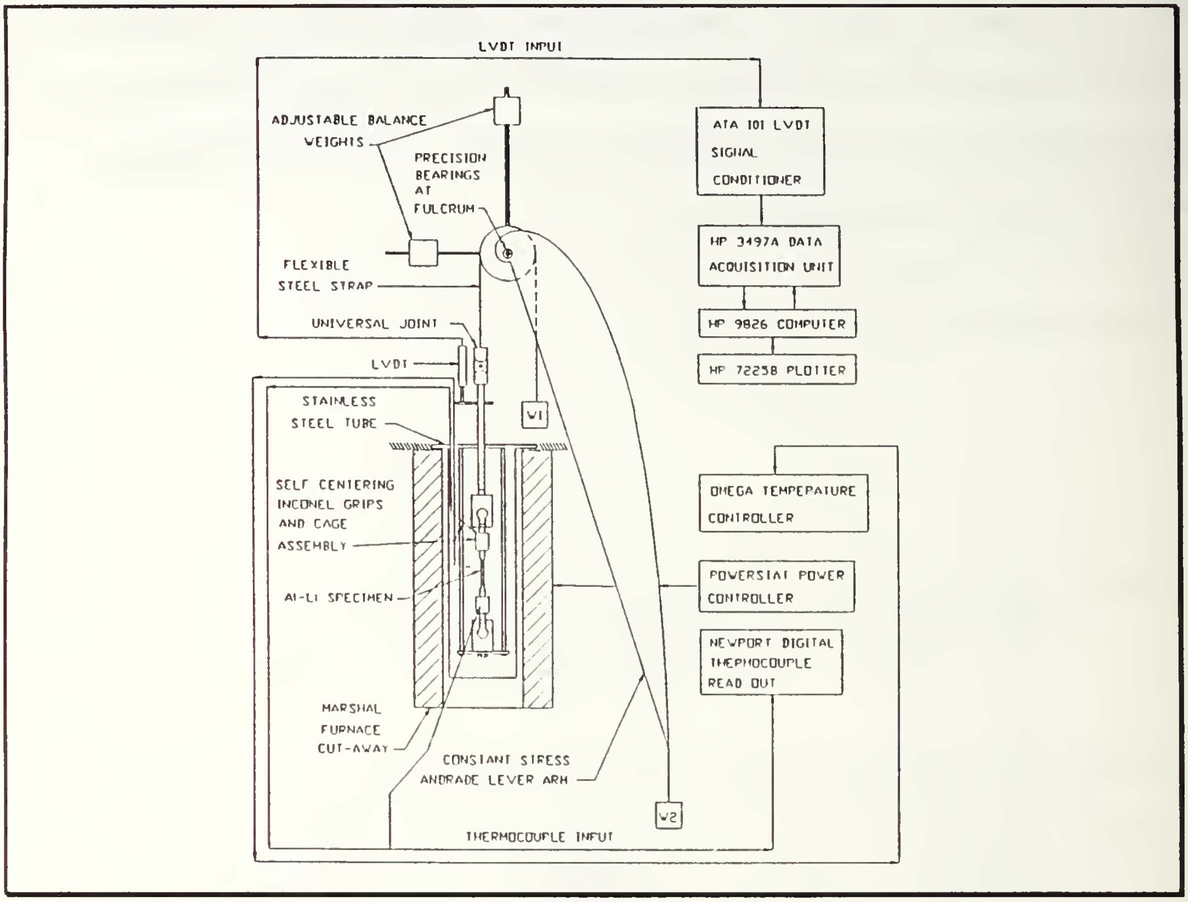

Figure 5. Diagram of Constant Stress Machine

This rotation decreases the moment arm of the applied load as the cross-sectional area of the specimen decreases with elongation, thus maintaining a constant true stress. The design of the arm is based on the assumption that the load train is rigid and the linkage displacement is taken up uniformly. The

machine is capable of transmitting loads between 1.5 and 222.5 Newtons (0.3 to 50 lbs) and at strains as high as 300 percent.

The contour of the lever arm was designed using Autocad in conjunction with the highly accurate graphical technique developed by Coghlan[Ref. 8]. The design used an effective gauge length of 13 mm (0.5 in) with an initial lever arm ratio of 10:1. The lever arm was constructed of 6.4 mm (0.25 in) thick 2024-T6 Aluminum and is attached to a 9.53 mm (0.375 in) diameter shaft rotating on a set of precision bearings. An adjustable counterbalance was affixed to the opposite end of the shaft, balancing the lever arm. This counterbalance in conjunction with another weight attached to the shaft to compensate for the weight of the load train, ensured that the only load sensed by the sample was that of the applied load.

A flexible 0.55 mm (0.02 in) thick steel strap follows the lever arm contour and hangs along the vertical tangent to the lever. A second flexible strap hangs tangent to a two inch radius disc centered at the fulcrum point which transmits the tensile load to the sample via the load train. The entire linkage was calibrated using a 50 lbf capacity interface load cell installed in the load train. The maximum stress variation through 300 percent elongation was 1.4 percent [Ref. 5].

Sample elongation was measured using a Schaevitz linear variable differential transformer (LVDT) with a 1 inch displacement. The core of the LVDT was attached to the upper specimen linkage. The 2.866 mv/v signal output from the LVDT is conditioned by a Schaevitz Model ATA 101 analog transducer amplifier. The amplifier voltage was measured by a Hewlett-Packard

(HP) Model 3497A Data Acquistion Unit controlled by an HP Model 9826 computer.

Marshall tubular furnaces were used for temperature control in conjunction with Eurotherm Model 808 digital temperature controllers. The temperature gradient in the furnaces was controlled and monitored similarly as with the Instron testing. Preheat and sample loading procedures were also similar.

Prior to the temperature stabilizing, the creep test program was started. The LVDT was zeroed (as determined with a digital multi-meter) in parallel with the amplifier (later, this step would be eliminated by a modification in the creep data acquisition program which zeroed the readings artificially). A precalculated weight in a plastic bag was carefully suspended from the lever arm by the flexible strap, and each test was allowed to continue to failure.

1. Features of the Software for the Constant Stress Tests

The software designed to run the creep tests was written in HP Basic 2.0 and featured a user friendly, menu-driven interface, see Appendix G. The software was designed to control two creep machines running simultaneously, and would plot and display on a video monitor the real time engineering strain vs time graphs for simultaneous tests. The algorithm was written to sample 5000 voltage and time data pairs for each test and then convert the voltage to engineering strain using 1 volt per 20% strain. Once the test was completed the menu gave the user the choice of plotting either true/engineering strain vs time graphs on the HP Model 7275B plotter, or of saving the accumulated data to one of three floppy disc drives. If desired, the program also prints a table with the reading number, the percent strain and the time of the reading on the HP Think Jet printer.

E. TEMPERATURE CYCLING TESTS

The temperature cycling tests were similar to the creep tests with the exception that the temperature was raised 10^{o}C above the initial test temperatures and after from four to eight hours, and was subsequently returned to the initial test temperature. This procedure was repeated until failure for each sample. The load and cycle times were such that each test would cycle several times over a two to four day period.

Later receipt of Eurotherm Model 808 programmable digital temperature controllers allowed precise control of temperature ramp, level, and dwell time. The PID features of these controllers also were adjusted to eliminate temperature over-shoot.

F. DATA REDUCTION

For the Instron tests, the raw data was obtained manually from the Instron strip chart recorder. The data from the plastic region were converted to true stress strain data by a program written in Basic for the NPS Mainframe computer (see Appendix G). The program was written to calculate a correction factor to account for mechanical slippage while testing. These data points were plotted using the Easyplot graphics routine on the NPS mainframe computer. The peak true stress from the above data was paired with the known applied strain rate to determine a single data point.

For the creep tests, the data was stored to 5 1/4 in floppy disc and output on the plotter. The creep rate in the secondary region was graphically determined from the true strain vs time creep curve and was paired with the known applied stress to constitute a single data point.

The temperature cycling test data was reduced in a similar manner as the creep tests. Additionally, the strain rate vs true strain graphs were plotted using a computer program written in HP Basic 2.0. This data reduction program was designed to be user-friendly and is menu-driven (see Appendix G). The menu choices included several types of graphs, true strain tables, strain rate tables, and calculation of activation energy. An example of the tables produced is in Appendix F.

The activation energies for the alloy were calculated from temperature cycling tests by graphical differentiation of the creep curve and were compared to the values of the activation energy for pure Al.

G. OPTICAL MICROSCOPY

Samples were mounted in Sample-Quik, manually ground to 600 grit, and polished with 3μm diamond paste. The samples were then electro-polished in Keller's reagent at 14 volts for 12 seconds, and anodized in Baker's solution at 14 volts for 60 seconds. The temperature of both processes was between -20 and -24^{o}C. Optical micrographs were taken at various magnifications on a Zeiss optical microscope under plane polarized light.

IV. RESULTS AND DISCUSSION

A. MICROSCOPY

Optical microscopy was conducted by Ellison [Ref. 6] on as-rolled samples and on samples annealed at 500°C prior to creep testing. He reports that the as-rolled material exhibited grains somewhat elongated in the direction of rolling, consistent with the processes of fabrication. Subsequent annealing results in a microstructure that has large, equiaxed grains, which demonstrated that the anneal at 500°C for 15 minutes was sufficient to remove the effects of the rolling [Ref. 6]. Figure 6, presents a micrograph of the grip section from a sample deformed at 300°C.

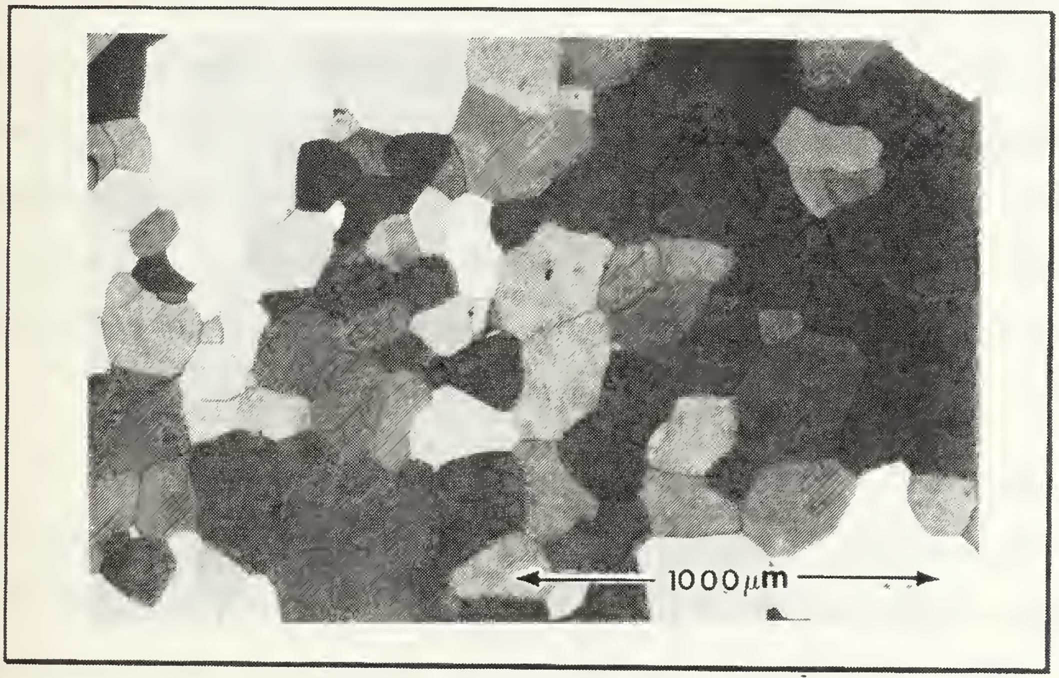

Figure 6. Optical Micrograph of 300°C Sample: Grip Section at 50x

It shows an equiaxed grain structure. Comparison with previous microscopy [Ref. 6] reveals the same microstructure and suggests little precipitation, either in grain interiors or upon grain boundaries, as a result of heating to 300°C.

B. CONSTANT EXTENSION RATE TESTS

Figure 7 summarizes typical results of Instron tests of the Al-2.0%Li alloy conducted at 300°C. Note that the material tested at the faster strain rate achieves a higher yield strength, rate of strain hardening and maximum stress than that at the slower rate. Under these conditions, strain hardening predominates the stress strain curve and there is no well-developed, steady-state behavior.

Figure 8 summarizes the results of Instron tests conducted at 450°C, and comparison to Figure 7 illustrates the effect of temperature. Note again that the material tested at the faster stain rate achieves a higher yield strength and maximum stress than that at the slower rate. However, under these conditions, softening of the material clearly predominates the stress strain curve. Deformation appears to occur at a nearly constant stress for strains above 10%, therefore, suggesting an approximate steady-state behavior of the alloy.

C. CONSTANT STRESS TESTS

In this portion of the research, specimens were tested at different stresses and secondary creep rates were calculated by graphical differentiation of the creep curves. Each specimen was tested to failure at a constant stress. Figure 9, in which true strain, ε, is plotted against time, shows a typical creep curve obtained at a temperature of 300 °C.

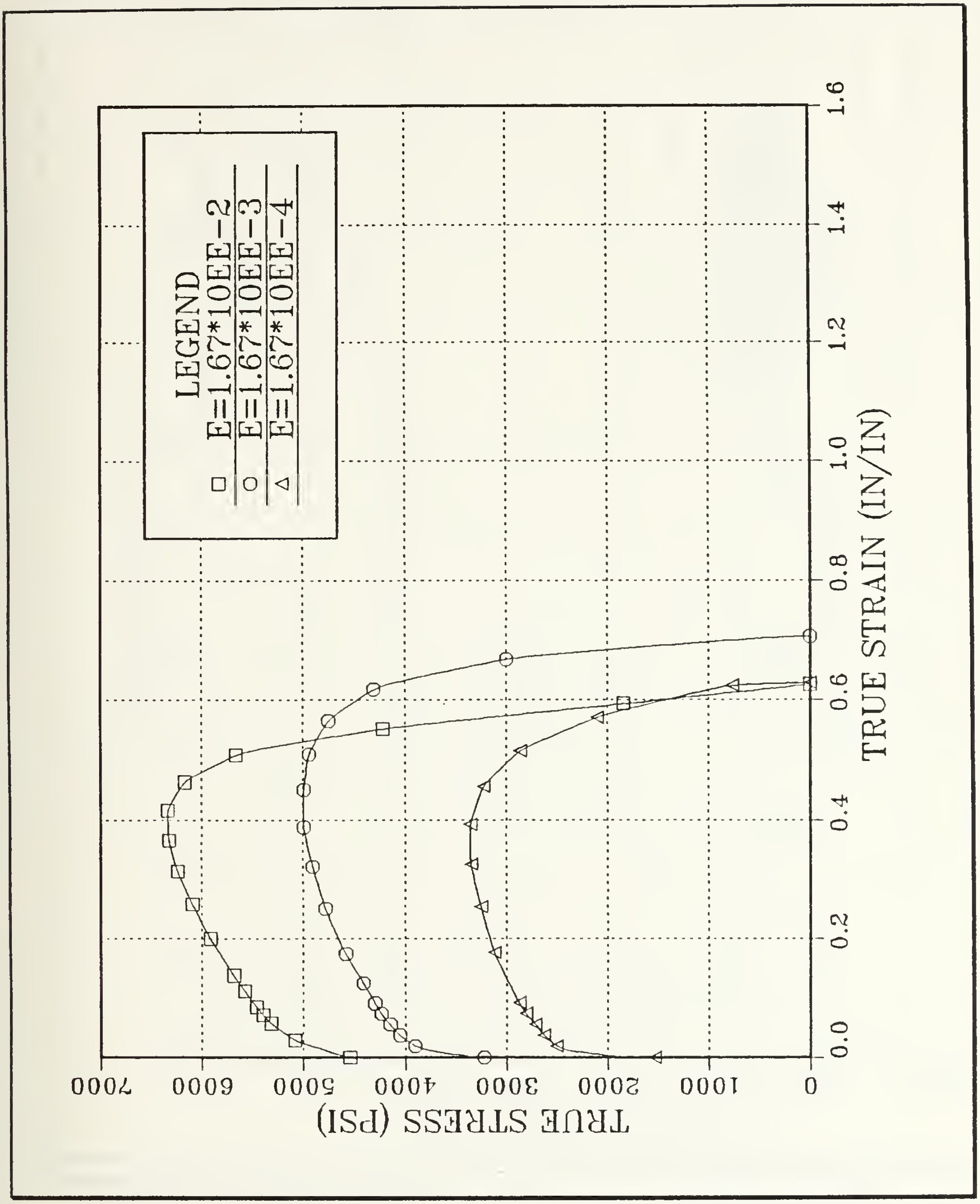

Figure 7. Stress Strain Curves at 300°C for Various Strain Rates

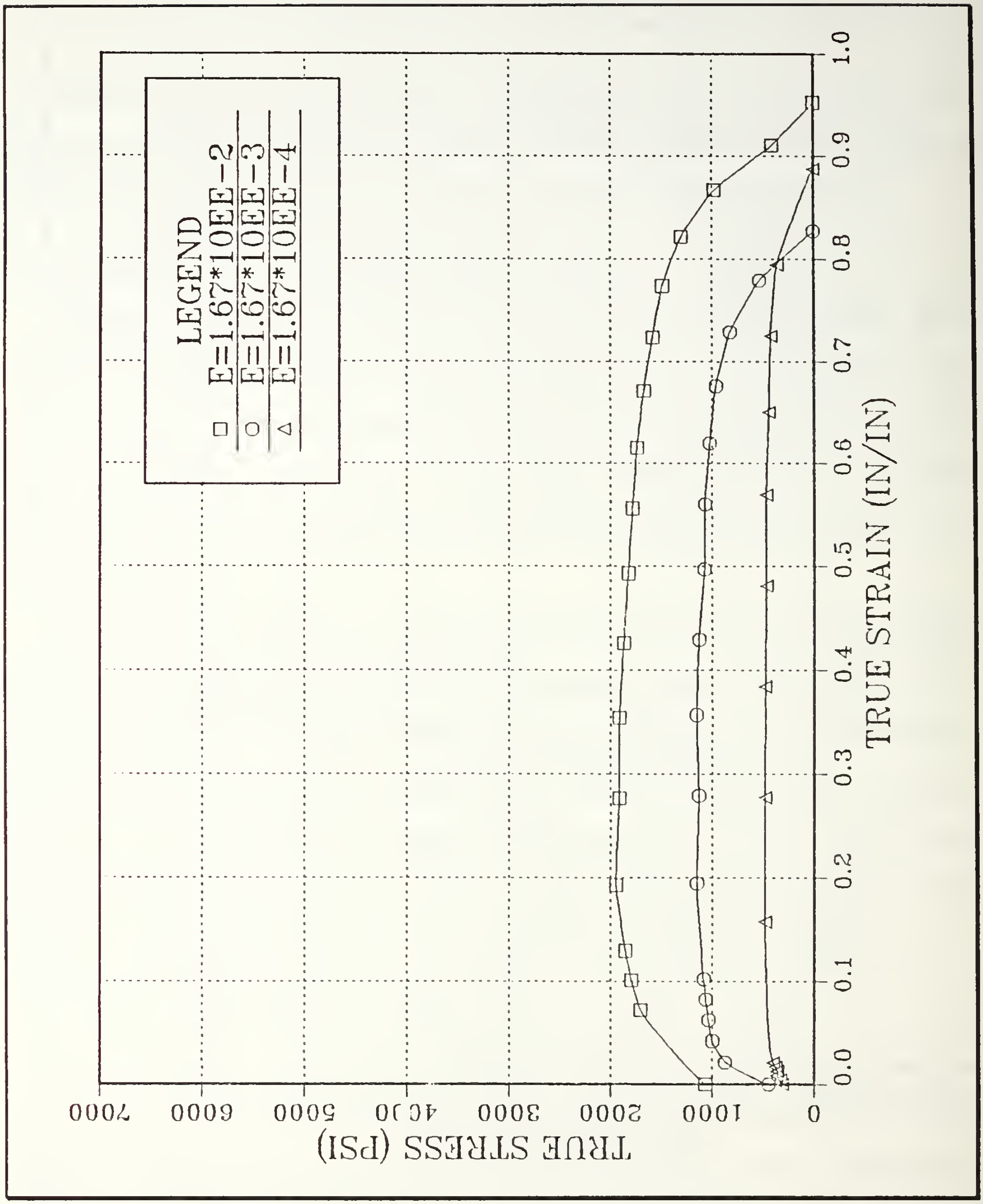

Figure 8. Stress Strain Curves at 450°C for Various Strain Rates

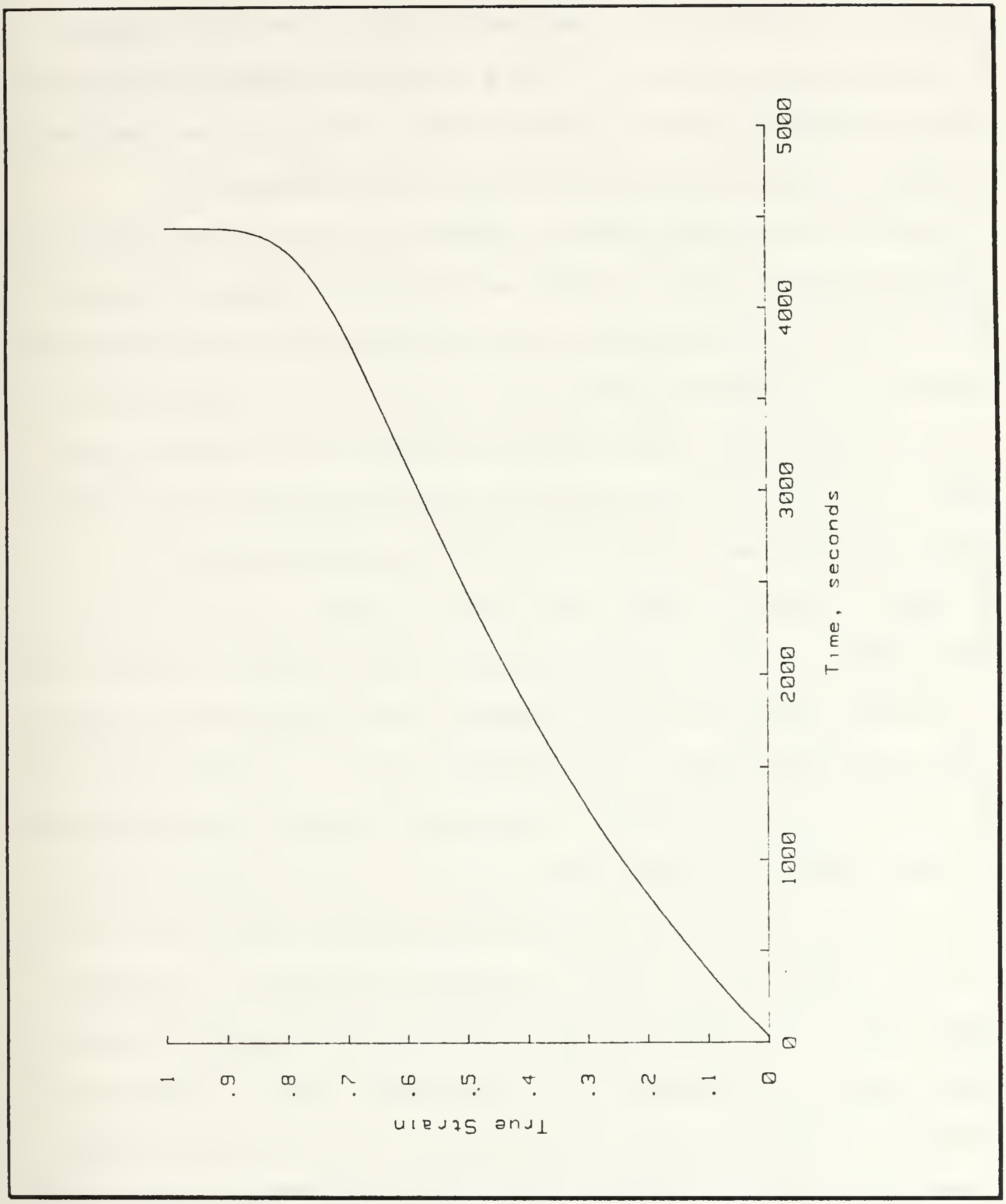

Figure 9. Creep Curve at 500°C for a Stress of 2.65 MPa:

$\dot{\varepsilon}_{min} = 1.50 \times 10^{-4}$ sec^{-1}

As seen in the figure, the creep curve exhibits three main features: a decelerating primary stage up to ~ 50%, a well-defined secondary stage and an accelerating tertiary stage prior to sample failure. The shape of the creep curve is, therefore, similar to those reported for pure Al by Sherby.[Ref. 1]

The effect of the applied stress at a higher temperature is demonstrated by comparing Figure 9, tested at 500°C and 2.65 MPa, to Figure 10, tested at 500°C and 5.48 MPa (note that the creep results are represented on different time axes.). For a greater applied stress, the alloy sustains a higher creep rate. Also, the primary stage is less extensive at 500°C when compared to that at 300°C. For all tests in this investigation, creep rates increased as the applied load increased and creep rates increased as the temperature increased.

Figure 11 shows a typical creep rate, $\dot{\varepsilon}$, versus true strain, ε, curve corresponding to the strain-time curve shown in Figure 9 above. The creep rate curve exhibits three main features: a distinct parabolic shape with the primary creep rate decreasing slowly, a clear inflection point at $\varepsilon \sim 0.58$ where the creep rate goes through a minimum and a pronounced increase in the tertiary creep rate prior to failure. The shape of the creep rate curve is, therefore, similar to those reported by Smith [Ref. 9]. The jagged appearance of the curve is due to the effects of quantization errors in the acquisition equipment. The analog-to-digital (a/d) converter must represent a continuous-time signal in a discrete manner and may not distinguish close, yet different, values of voltages sent it from the LVDT and its amplifier. The threshold of each level must be enough to cause the a/d converter to ascend to the next discrete level. Additional errors are introduced since the voltage values are truncated when each value is converted to binary code for mass storage on the floppy disc.

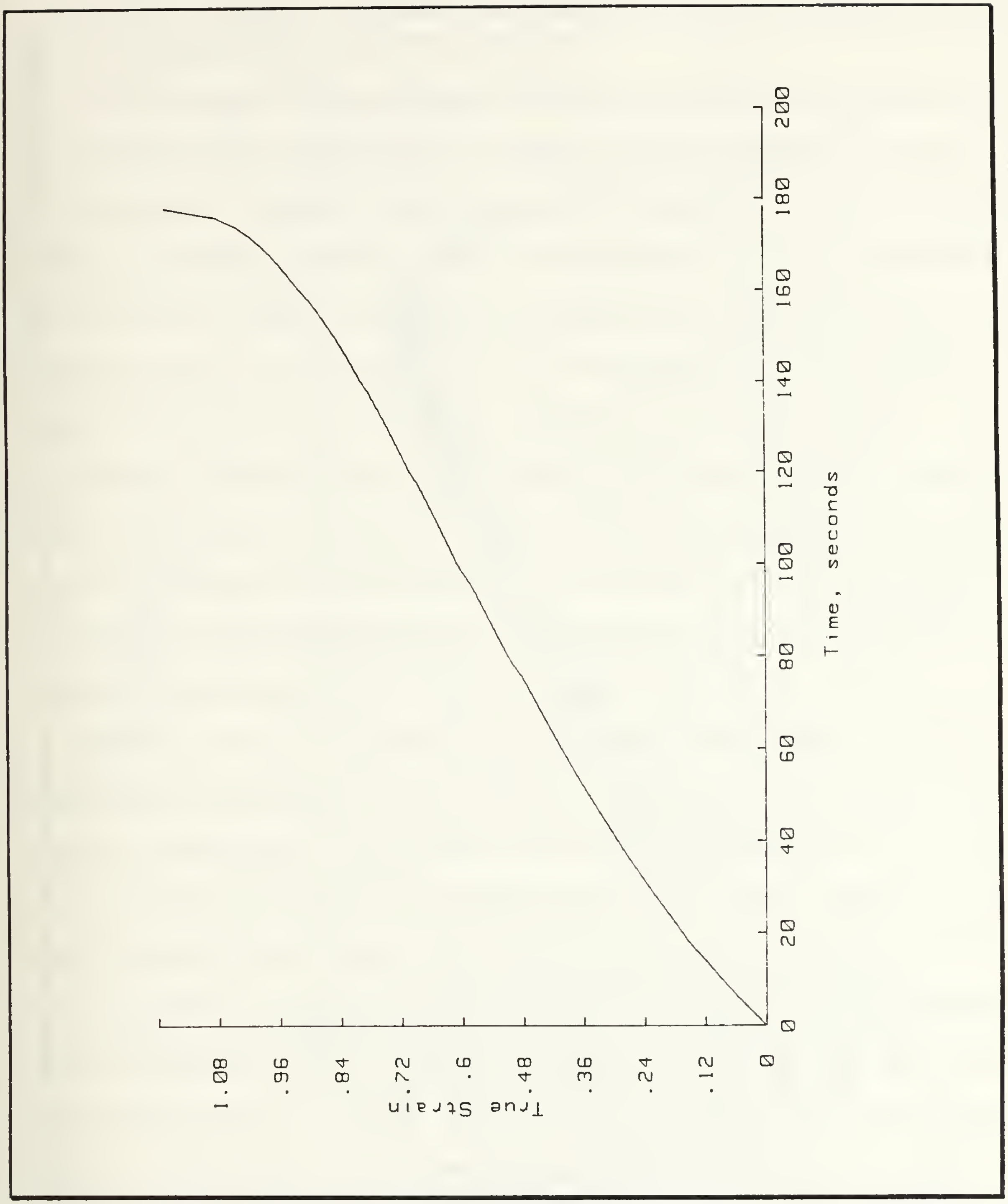

Figure 10. Creep Curve at 500°C for a Stress of 5.48 MPa:

$\dot{\varepsilon}_{min} = 4.83 \times 10^{-3}\ sec^{-1}$

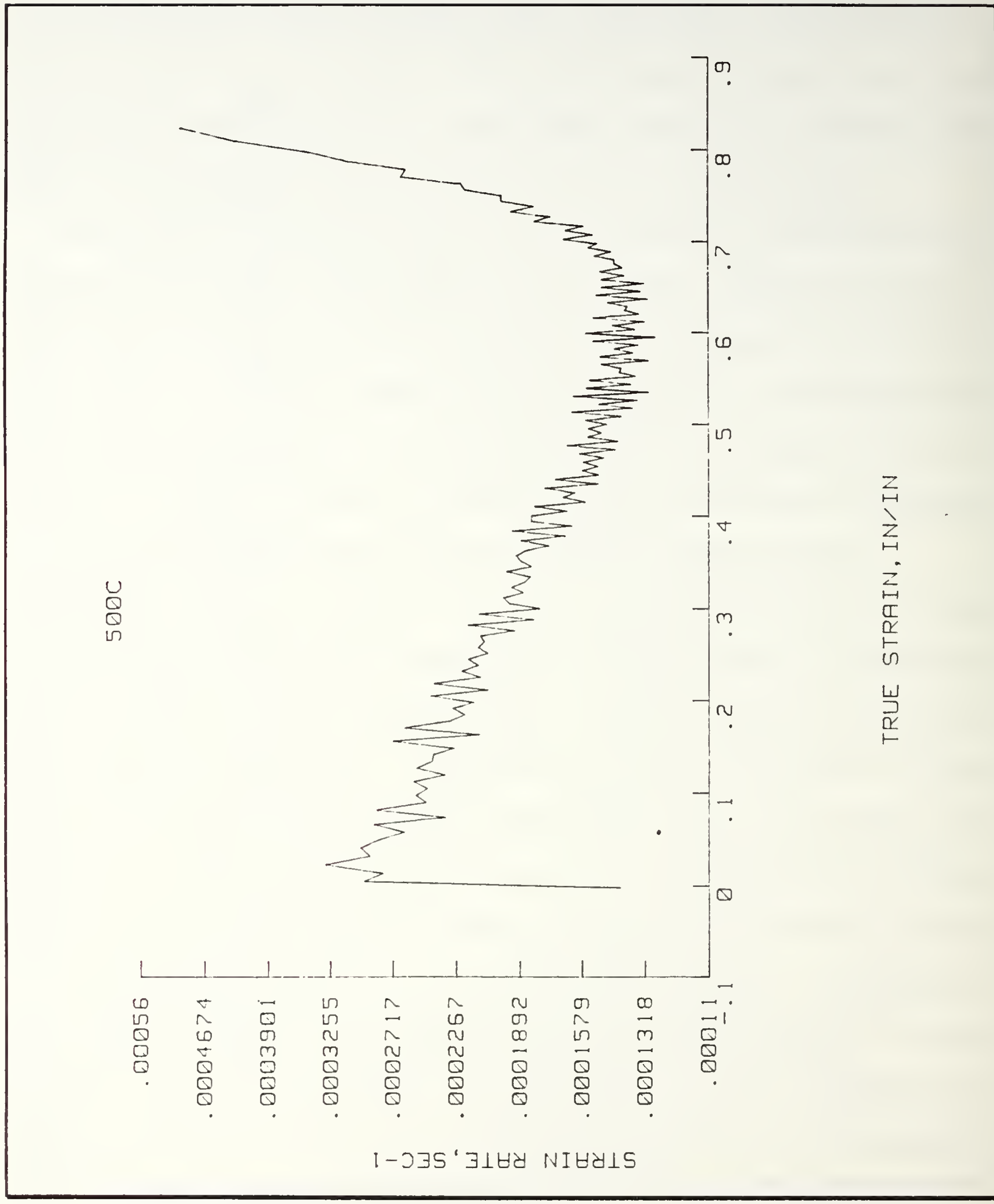

Figure 11. Creep Rate Curve at 500°C for a Stress of 2.65 MPa:

$$\dot{\varepsilon}_{min} = 1.43 \times 10^{-4} \text{ sec}^{-1}$$

D. TEMPERATURE CYCLING TESTS

In this procedure, several identical specimens were crept at a constant stress, σ, while the initial temperature, T_1, is rapidly increased. Within 10 minutes of the temperature increase, sufficient strain had accumulated to ascertain the presence of the new creep rate. This new temperature level, T_2, was held for several hours. Finally, the increased temperature is rapidly decreased to its original value of T_1 and the cycling of the temperature in this manner is continued through steady-state and up until failure. A typical example for the application of this procedure at 350^{o}C is shown in Figure 12, in which the true strain, ε, is plotted as a function of time. Examination of these data reveals that there is a similarity between temperature cycling creep curves and isothermal creep curves and that the duration of the temperature excursion from T_1 to T_2 is nominal when compared to the overall duration of the test.

Figure 13 reveals a typical creep rate versus creep strain curve for the temperature cycling tests in which creep rate, $\dot{\varepsilon}$, is plotted as a function of creep strain, ε. Examination of the figure reveals three important points. First, the creep rate, after the temperature increase from 350 to 360^{o}C, increases and quickly reaches the new value. Second, in the minimum creep rate region, the creep rate after the temperature change from 350 to 360^{o}C reaches a value that essentially agrees with the original steady-state rate established before the temperature increase to 360^{o}C. Third, the creep transient after a temperature change, is identical to that of pure Al, as reported previously by Lytton *et al.*[Ref. 10]

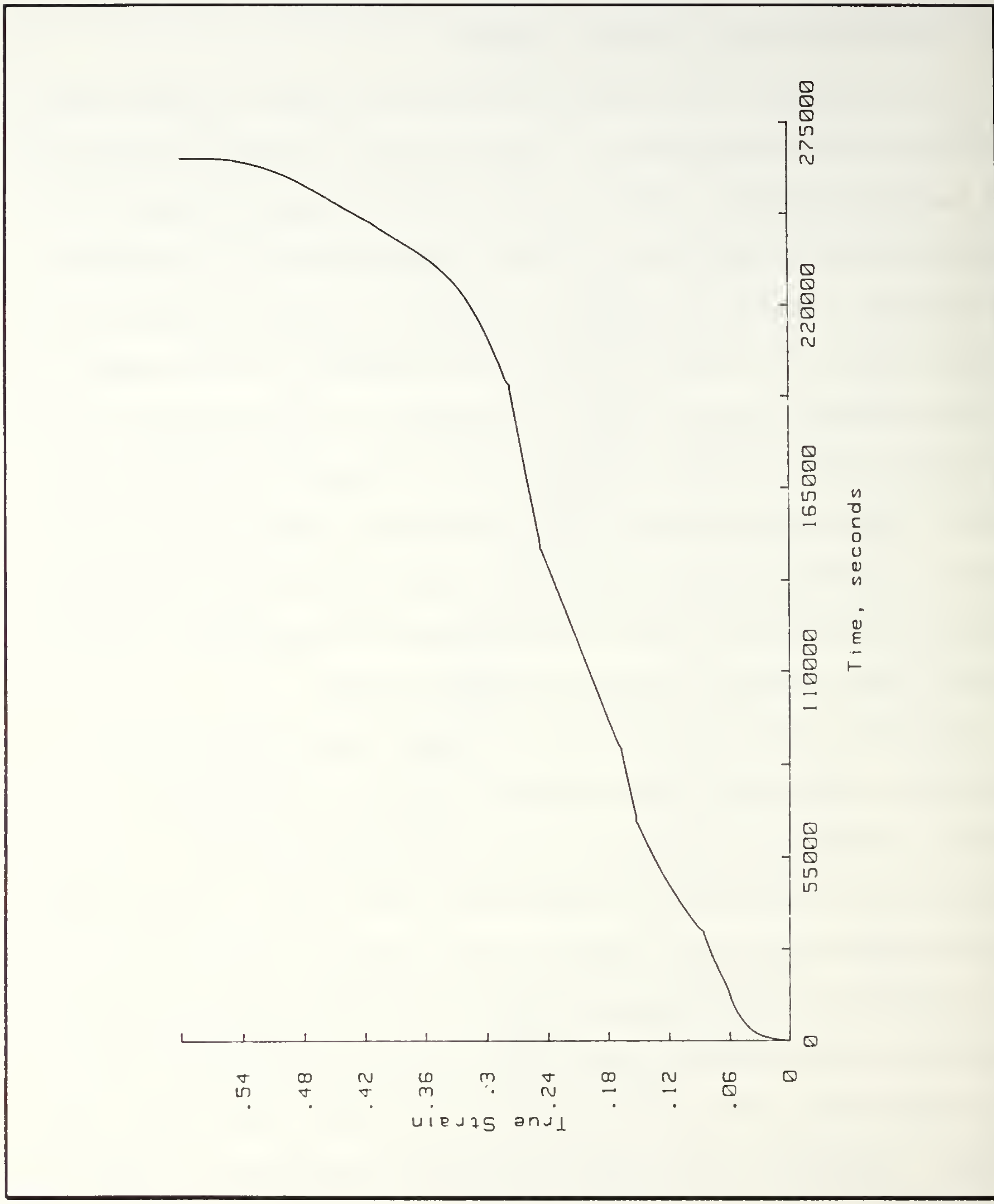

Figure 12. Creep Curve at 350-360°C for a Stress of 6.38 MPa:

$\dot{\varepsilon}_1 = 1.28 \times 10^{-6}\ \mathrm{sec}^{-1}$ & $\dot{\varepsilon}_2 = 6.55 \times 10^{-7}\ \mathrm{sec}^{-1}$

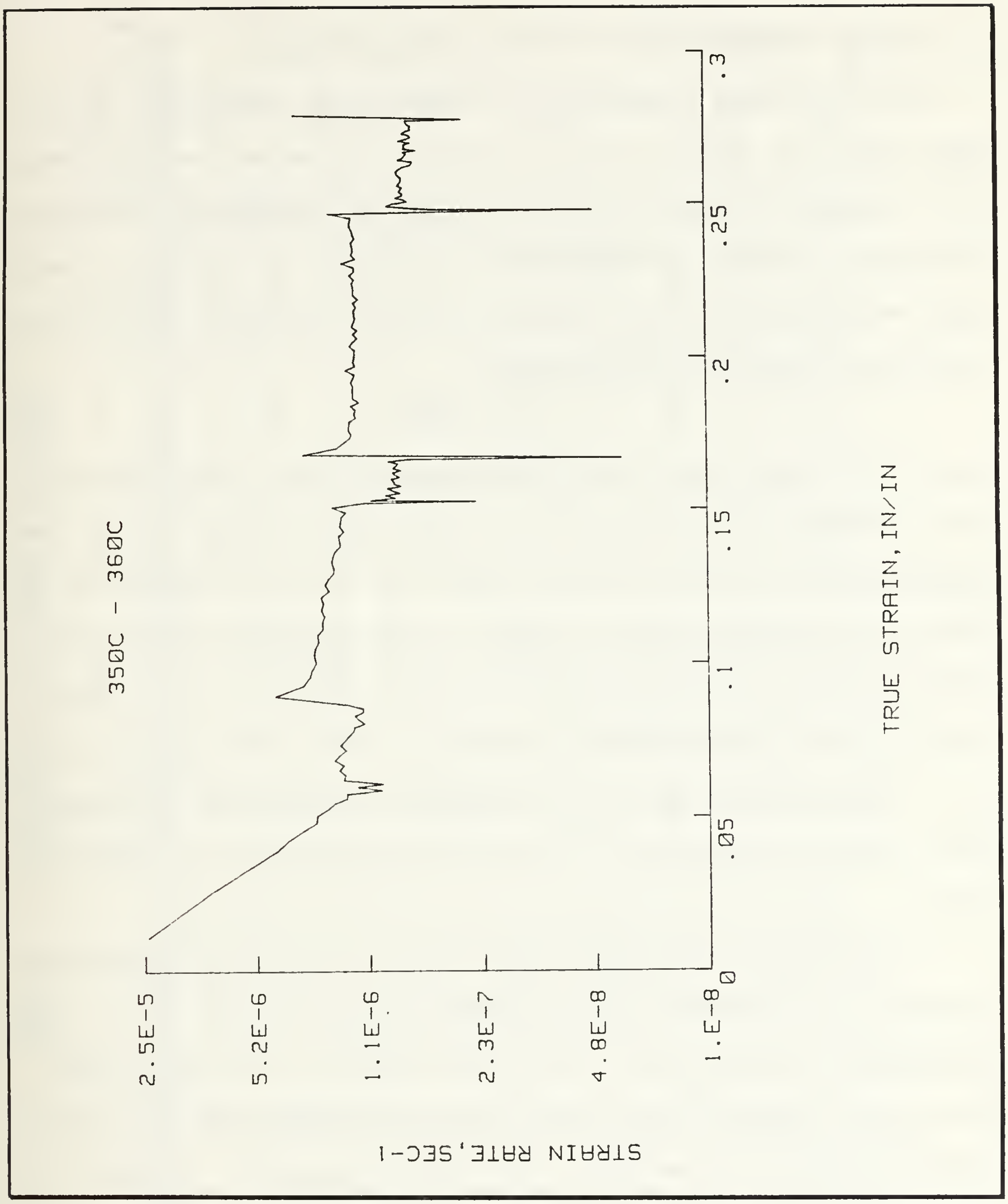

Figure 13. Creep Rate Curve at 350-360^{o}C for a Stress of 6.38 MPa: $\dot{\varepsilon}_1 = 1.28 \times 10^{-6}$ sec^{-1} & $\dot{\varepsilon}_2 = 6.55 \times 10^{-7}$ sec^{-1}

E. STRESS DEPENDENCE OF THE STRAIN RATE

The data of Table 2 summarize the results of the uninterrupted tests to failure and may be utilized to determine the stress and temperature dependence of the strain rate and thus facilitate determination of the underlying mechanisms of deformation. Sherby and Burke [Ref. 1] note that, for an intermediate stress range, the relationship between strain rate and stress at constant temperature can be described by the power-law relationship:

$$\dot{\varepsilon}_{min} = K\sigma^n \tag{4}$$

values of n for pure metals (Al) are usually equal to 5.The experimental values of log $\dot{\varepsilon}$ obtained in this research were plotted versus log σ for each test temperature. The results are shown in Figure 14. The stress exponent for Al-2.0%Li, as calculated from the slopes of the isothermal curves, shows dependence on temperature such that n is 6.7 at 300°C and 6.0 at 350°C. However, at 400, 450 and 500°C, n is relatively constant with values of 5.0, 4.8 and 4.9, respectively, and appears to be independent of temperature in this range. These n values, calculated from the data by linear regression, are compiled in Table 3.

For comparison purposes, data from Park *et al* [Ref. 11], who conducted creep tests of Al-2.1wt%Li in the temperature range of 500 to 560°C and utilizing double shear specimens, are plotted on Figure 14. Note that at 500°C the two data sets differ by a factor of 2 which is considered excellent agreement given the different test methods. The stress exponent for Al-2.1%Li, as estimated from the slope of the plot, is essentially independent of temperature and is close to a value of 4.6. The stress exponent from this investigation at

Table 2. SUMMARY OF Al-2.0%Li RESULTS

Type	#	Temp (^oC)	$\dot{\varepsilon}$ (sec^{-1})	σ (MPa)	log $\dot{\varepsilon}$	log σ	$\dot{\varepsilon}$ / D (m^{-2})	σ / E	% Elongation
Instron	1	300	1.67×10^{-2}	43.7	-1.78	1.64	1.01×10^{15}	7.24×10^{-4}	87.6
Instron	16	300	1.67×10^{-3}	34.4	-2.78	1.54	1.01×10^{14}	5.71×10^{-4}	110
Instron	27	300	1.67×10^{-4}	23.1	-3.78	1.37	1.01×10^{13}	3.83×10^{-4}	91.0
Creep	3	300	6.40×10^{-5}	21.2	-4.19	1.33	3.87×10^{12}	3.52×10^{-4}	152
Creep	4	300	3.25×10^{-5}	19.0	-4.49	1.28	1.97×10^{12}	3.15×10^{-4}	144
Creep	5	300	4.24×10^{-6}	13.0	-5.38	1.11	2.54×10^{11}	2.15×10^{-4}	119
Instron	19	350	1.67×10^{-2}	31.1	-1.78	1.49	9.12×10^{13}	5.43×10^{-4}	80.0
Creep	11	350	1.90×10^{-3}	21.2	-2.72	1.33	1.04×10^{13}	3.70×10^{-4}	141
Instron	17	350	1.67×10^{-3}	21.4	-2.78	1.33	9.12×10^{12}	3.73×10^{-4}	103
Instron	25	350	1.67×10^{-4}	13.6	-3.78	1.13	9.12×10^{11}	2.37×10^{-4}	95.0
Creep	13	350	8.88×10^{-5}	12.9	-4.05	1.11	4.85×10^{11}	2.24×10^{-4}	155
Creep	26	350	1.93×10^{-6}	7.00	-5.71	0.85	1.05×10^{10}	1.22×10^{-4}	88.0

Table 2. (Continued)

Type	#	Temp (^oC)	$\dot{\varepsilon}$ (sec^{-1})	σ (MPa)	log $\dot{\varepsilon}$	log σ	$\dot{\varepsilon}$ / D (m^{-2})	σ / E	% Elongation
Instron	21	400	1.67×10^{-2}	22.2	-1.78	1.35	1.18×10^{13}	4.05×10^{-4}	103
Instron	20	400	1.67×10^{-3}	14.4	-2.78	1.15	1.18×10^{12}	2.56×10^{-4}	99.0
Instron	22	400	1.67×10^{-4}	8.71	-3.78	0.94	1.18×10^{11}	1.59×10^{-4}	93.0
Creep	23	400	9.00×10^{-5}	7.10	-4.05	0.85	6.34×10^{10}	1.29×10^{-4}	167
Creep	24	400	1.71×10^{-5}	5.24	-4.49	0.72	1.20×10^{10}	9.54×10^{-5}	103
Creep	18	400	1.83×10^{-6}	3.76	-5.74	0.57	1.29×10^{9}	6.84×10^{-5}	88.0
Instron	38	450	1.67×10^{-2}	13.4	-1.78	1.13	2.02×10^{12}	2.58×10^{-4}	157
Instron	32	450	1.67×10^{-3}	7.96	-2.78	0.90	2.02×10^{11}	1.53×10^{-4}	134
Instron	53	450	1.67×10^{-4}	--	-3.78	--	2.02×10^{10}	-- $\times 10^{-4}$	143
Creep	35	450	4.43×10^{-5}	3.90	-4.35	0.59	5.35×10^{9}	7.50×10^{-5}	133
Creep	34	450	5.15×10^{-6}	2.46	-5.29	0.39	6.22×10^{8}	4.73×10^{-5}	80.0
Instron	45	500	1.67×10^{-2}	8.08	-1.78	0.91	4.34×10^{11}	1.61×10^{-4}	112

Table 2. (Continued)

Type	#	Temp (^oC)	$\dot{\varepsilon}$ (sec^{-1})	σ (MPa)	log $\dot{\varepsilon}$	log σ	$\dot{\varepsilon}$ / D (m^{-2})	σ / E	% Elongation
Creep	41	500	4.83×10^{-3}	5.48	-2.32	0.74	1.26×10^{11}	1.10×10^{-4}	194
Instron	51	500	1.67×10^{-3}	4.27	-2.78	0.63	4.34×10^{10}	8.54×10^{-5}	123
Creep	40	500	2.43×10^{-4}	3.67	-3.61	0.57	6.31×10^{9}	7.34×10^{-5}	119
Instron	52	500	1.67×10^{-4}	3.02	-3.78	0.48	4.34×10^{9}	6.04×10^{-5}	95.0
Creep	39	500	1.50×10^{-4}	2.65	-3.84	0.42	3.90×10^{9}	5.30×10^{-5}	131
Creep	46	500	1.49×10^{-4}	2.65	-3.83	0.42	3.87×10^{9}	5.30×10^{-5}	(arrested)
Creep	37	500	6.59×10^{-5}	2.25	-4.20	0.35	1.71×10^{9}	4.50×10^{-5}	67.0
Creep	44	500	1.20×10^{-5}	1.84	-4.92	0.27	3.12×10^{8}	3.68×10^{-5}	60.0
Creep	55	500	6.00×10^{-6}	1.63	-5.22	0.21	1.56×10^{8}	3.26×10^{-5}	56.0

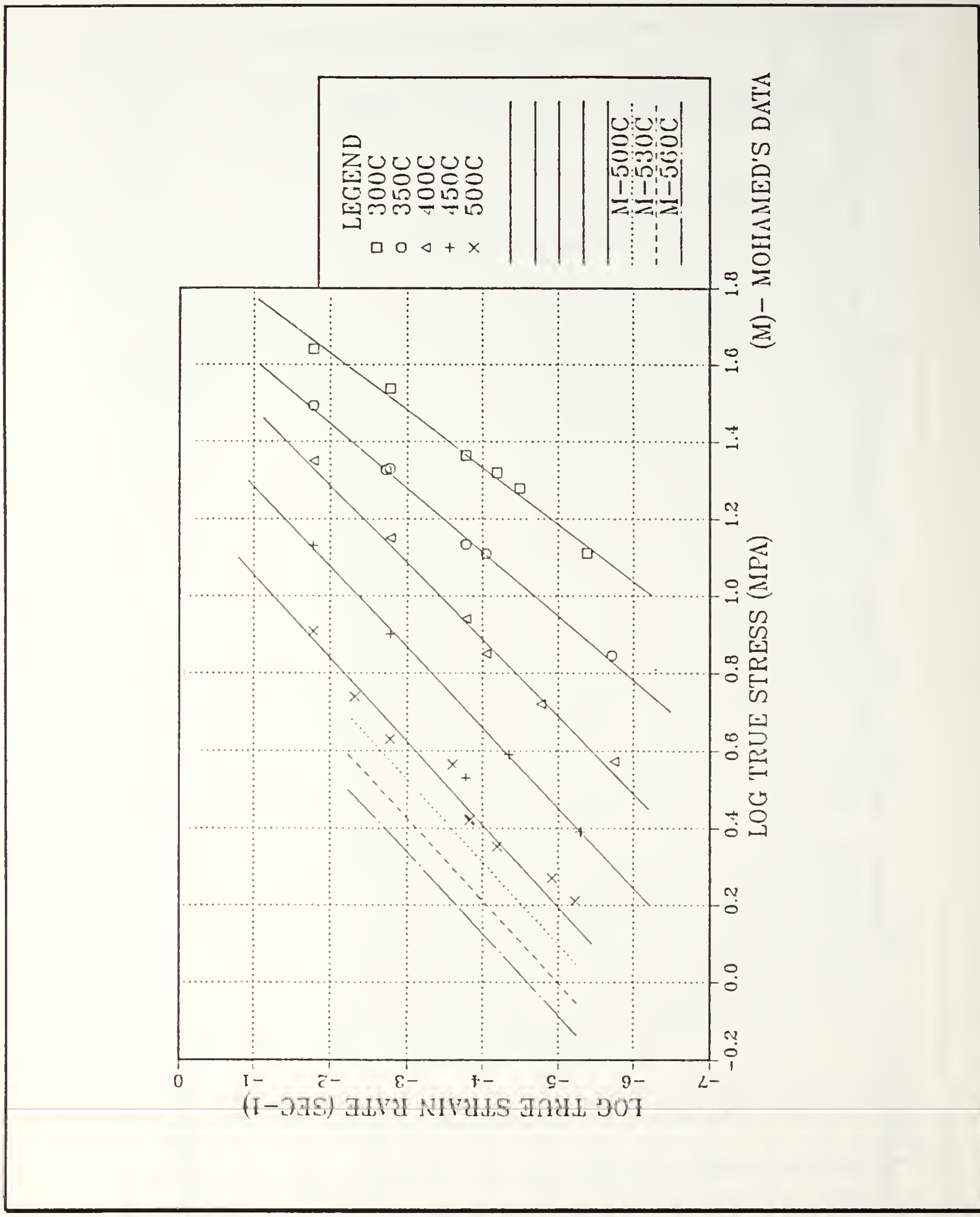

Figure 14. Log-Log Curves of Strain Rate Vs. True Stress

Table 3. STRESS EXPONENT

Temp (^{o}C)	Value of n
300	6.7
350	6.0
400	5.0
450	4.8
500	4.9

500^{o}C is 4.9 and also compares well with the value reported in the work of Park *et al.*[Ref. 11].

From the n values obtained in this investigation, it is surmised that the mechanisms of creep in the temperature range of 400 to 500^{o}C are similar to that of pure Al, which deforms by glide and climb of dislocations, with diffusion-controlled climb determining the overall rate of straining.

F. MICROSTRUCTURAL EVOLUTION DURING CREEP

Optical microscopy was conducted on fractured samples from the 300^{o}C and the 500^{o}C creep tests. Figure 15(a), a photo-micrograph of the gauge section of a coupon tested at 300^{o}C, was taken at a low magnification of 50x. It illustrates the elongated grains due to creep in the direction of straining. Sub-structures have formed within the grains, as evidenced by the mottled contrast. This is in accordance with class II deformation behavior, and can be distinguished more readily in Figure 15(b), a micrograph of the same region, but at a magnification of 200x. The sub grains are well delineated in the grain to the right of center of

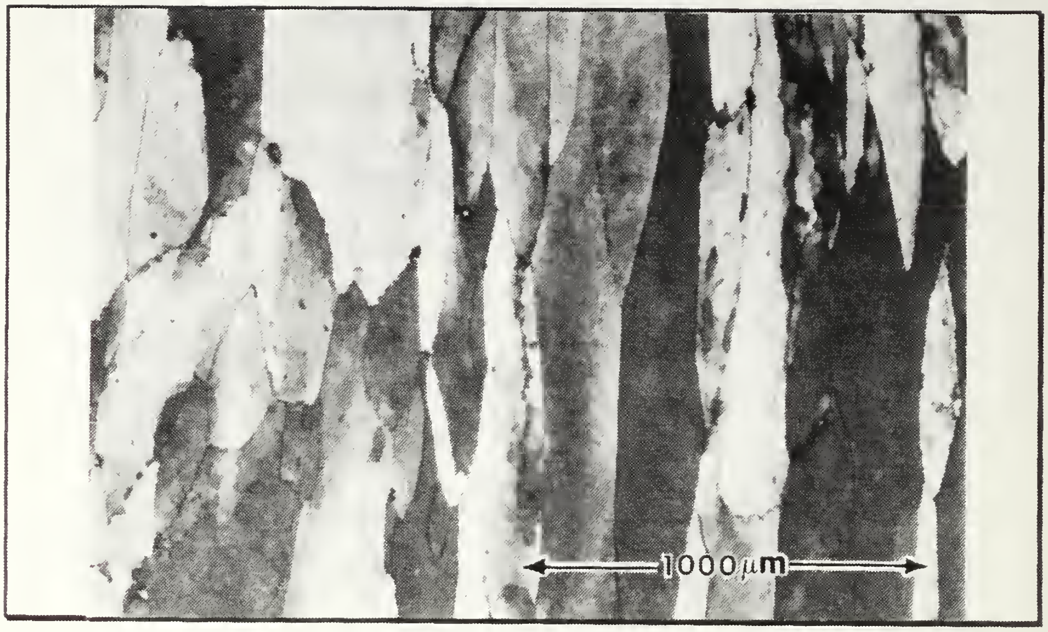

Figure 15(a). Optical Micrograph of 300°C Sample: Gauge Section at 50x

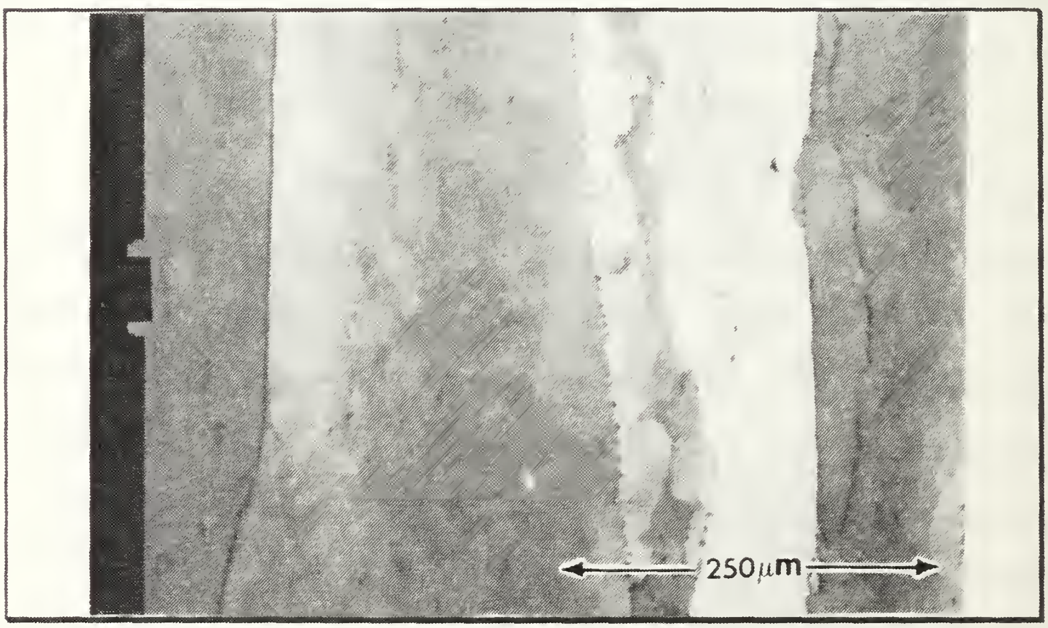

Figure 15(b). Optical Micrograph of 300°C Sample: Gauge Section at 200x

the field of view. Intergranular precipitation is also evident and likely consists of δ' phase on the prior boundaries of the solid solution.

Figure 16 shows a micrograph of the grip section of a sample crept at 500°C and was obtained at 50x. Larger grains due to grain growth at the higher temperature are evident. Figure 17 is a micrograph of this 500°C sample's gauge section, also at a magnification of 50x. Grain growth due to temperature and strain is evident. A coarser subgrain structure (when compared to the sample deformed at 300°C) is also evident in this micrograph and appears as irregular grain boundaries.

G. ACTIVATION ENERGY FOR CREEP

The data of Table 4 summarize the results of the temperature cycling tests and may be utilized to determine the stress and temperature dependence of the activation energy for creep, Q_c. Assuming creep is thermally activated and follows an Arrhenius temperature dependence at constant stress, a value for Q_c can be obtained from equation 8. Determination of Q_c was accomplished by the previously described technique of evaluating the steady-state creep rate preceeding and following a small, abrupt change in temperature. Temperature differences of 10°C were used. The creep rates were determined by graphical differentiation of the strain versus time curves. All activation energies reported in this paper were plotted in terms of the mean test temperature [Ref. 10] defined as:

$$\frac{1}{T} = \frac{1}{2}\left(\frac{1}{T_1} + \frac{1}{T_2}\right) \qquad (12).$$

The results are summarized graphically in Figure 18. Values of Qc at 300 and 350°C are 47.4 and 52.3 kcal/mole, respectively. The activation energy, Q_c,

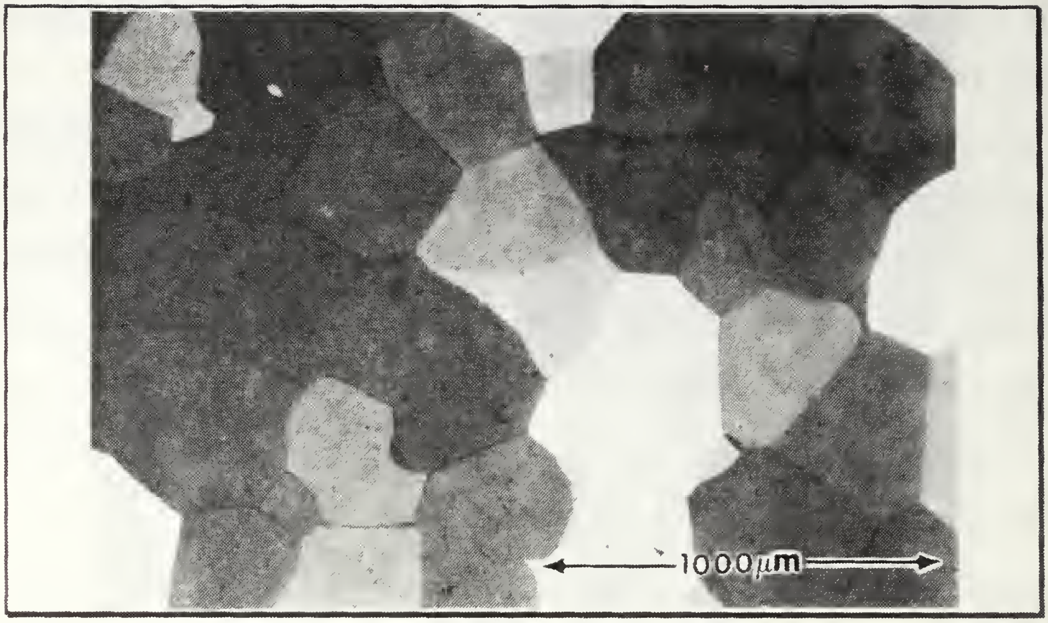

Figure 16. Optical Micrograph of 500°C Sample: Grip Section at 50x

Figure 17. Optical Micrograph of 500°C Sample: Gauge Section at 50x

Table 4. SUMMARY OF Al-2.0%Li TEMPERATURE CYCLING RESULTS

#	Temp (^oC)	Mean Temp (^oC)	$\dot{\varepsilon}_L$ (sec^{-1})	$\dot{\varepsilon}_H$ (sec^{-1})	Q_c (kcal/mole)
48	300-310	305	2.10×10^{-6}	4.30×10^{-6}	47.4
28	350-360	355	1.28×10^{-6}	6.55×10^{-7}	52.3
29	400-410	405	1.18×10^{-6}	2.22×10^{-6}	57.5
30	400-410	405	3.98×10^{-7}	7.31×10^{-7}	55.3
34	450-460	455	5.51×10^{-6}	8.69×10^{-6}	54.9
54	470-480	475	1.75×10^{-6}	2.52×10^{-6}	40.4
36	500-510	505	1.51×10^{-6}	1.99×10^{-6}	33.1

reaches its maximum value of 56.4 kcal/mole at 400^{o}C and then drops rapidly at 470 and 500^{o}C to values of 40.2 and 33.1 kcal/mole, respectively. Note that Q_c for pure Al in the temperature range 300 to 500^{o}C (573 to 773K) is constant at approximately 35.5 kcal/mole [Ref. 10].

Therefore, although the Al-2.0%Li alloy exhibits a similar stress dependence and formation of subgrain structures as observed in pure Al, the values of Q_c are appreciably higher. Table 5 is a compilation of activation energy results for this alloy. The data were obtained by three different computational methods. The first method used graphical differentiation directly applied to the individual creep curves. The second method involved use of linear regression applied to the creep rate versus creep strain curves. The third method calculated Q_c from the difference between the isothermal log $\dot{\varepsilon}$ vs. log σ plots for data obtained at constant stress. All methods involved similar values of strain rate which were then employed with equation 8 for determination of Qc. The values from the

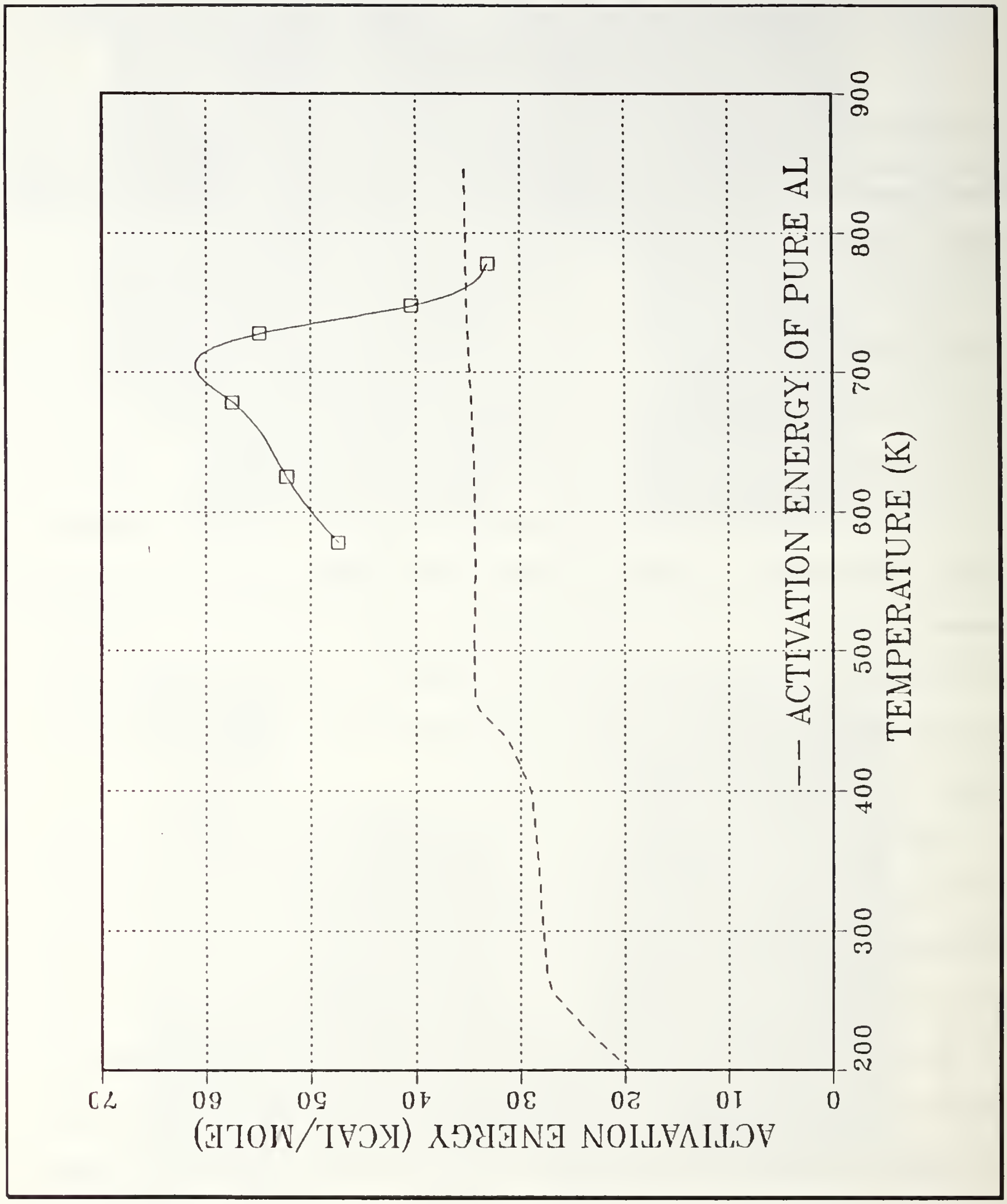

Figure 18. Al-2.0%Li Activation Energy Curve Compared to Pure Al

direct analysis of the creep curves and from the creep rate curves (i.e. from the differentiated creep curves) yield close agreement, as expected. Figure 19 gives further insight into the behavior of the activation energy for the Al-Li system. This figure graphically compares Qc for Al with 0.5, 1.0, and 2.0wt% Li additions. The data for the 0.5 and 1.0% Li additions are taken from the NPS study by Taylor [Ref. 5]. As Li content increases, the observed activation energy becomes progressively higher within the temperature interval 600 to 725K. The peak activation energy values are in order of Li addition: Qc for Al-2.0%Li peaks at 56.4 kcal/mole at 700K; Qc for Al-1.0%Li peaks at 54 kcal/mole and ~700K; and Qc for Al-0.5%Li peaks at 51 kcal/mole at 700K to 750K.

Table 5. SUMMARY OF Al-2.0%Li ACTIVATION ENERGY RESULTS IN KCAL/MOLE

#	Temp (^{o}C)	Mean Temp (^{o}C)	Creep Curves	Creep Rate	Log-Log Curve
48	300-310	304.92	47.4	45.9	42.5
28	350-360	354.93	52.3	50.9	55.9
29	400-410	404.94	57.5	55.6	49.0
30	400-410	404.94	55.3	62.7	49.0
34	450-460	454.95	54.9	54.6	54.4
54	470-480	474.95	40.4	*	--
36	500-510	504.95	33.1	*	--
* Note: these values were not obtained due to limits in the data acquisition system					

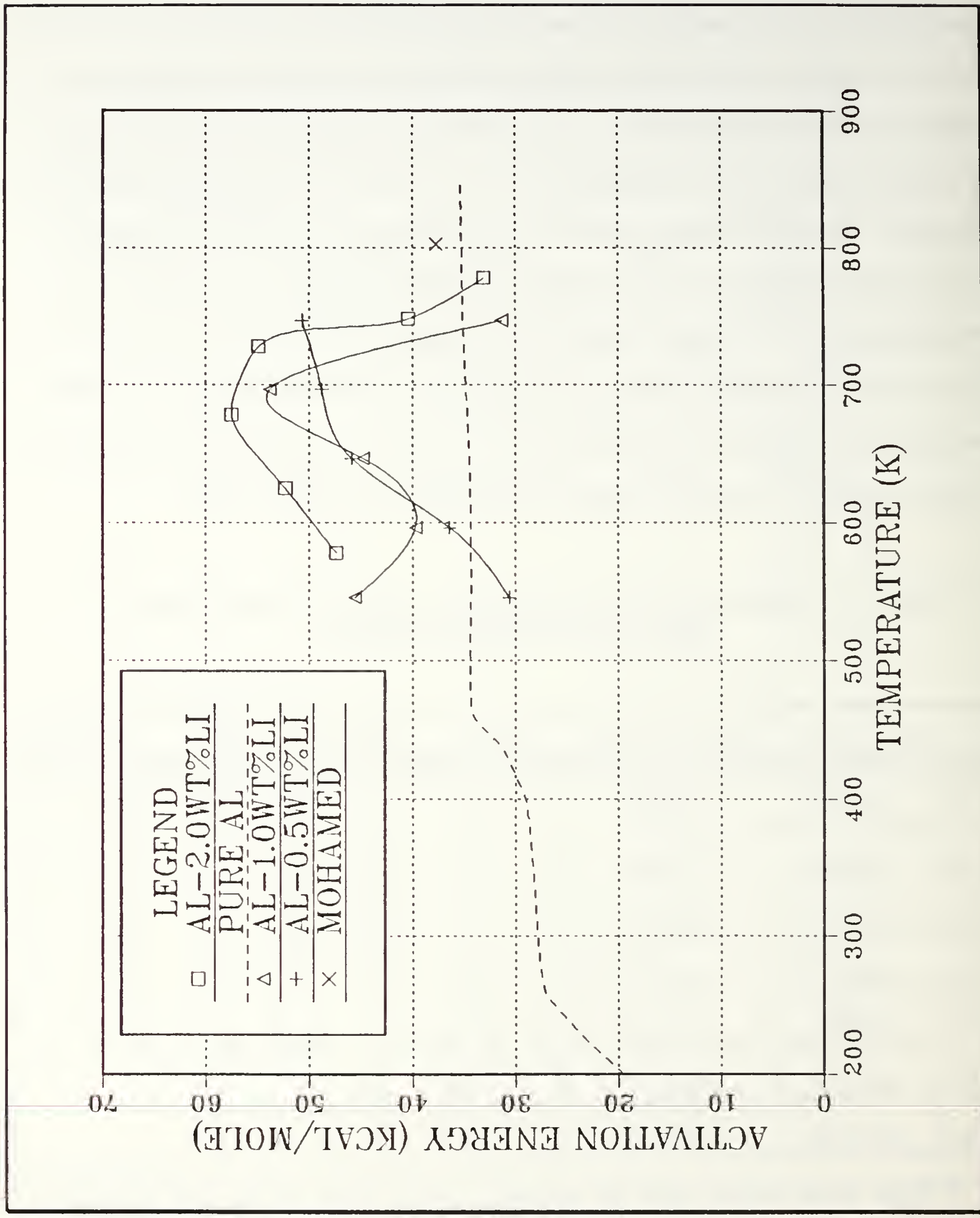

Figure 19. Activation Energy Versus Temperature for Al with 0.5, 1.0, and 2.0% Li Additions

H. NORMALIZED RESULTS

Further insight into the behavior of the Al-2.0%Li can be obtained by re-plotting the data as $\dot{\varepsilon}/D$ vs. σ/E on double logarithmic axes, as shown in Figure 20. Diffusion and modulus data were those for Al because data for Al-2.0%Li was unavailable. The data appears similar to the Al data as modelled by the Wu-Sherby relationship [Ref. 12]:

$$\dot{\varepsilon}_{min} = \frac{K\,D_{eff}}{\alpha^n\,b^2}\left(\sinh \alpha\frac{\sigma}{E}\right)^n \qquad (11)$$

where $K = 2 \times 10^{12}$, b = Burger's vector (2.8×10^{-10}m), $\alpha = 2600$ and $n = 5$. The effective diffusion coefficient, D_{eff}, is essentially the lattice diffusion coefficient, D_l, modified to account for the enhancement of diffusion resulting from pipe diffusion. The stress dependence of the data is in close agreement with that of equation 11. However two observations can be made: as temperature decreases, the degree of alloy strengthening relative to Al increases; and, as the strain rate at a specific temperature decreases, the degree of alloy strengthening increases. This suggests that the temperature dependence of the normalizing values for the alloy is different from the temperature dependence of those values for the pure metal.

Stacking fault energy and modulus are a function of temperature. If these functions for the alloy are the same as for the pure metal, then one would expect little or no variation in the normalized data for the two cases. However, as noted earlier, the activation energy for the alloy from 300 to 450^{o}C is appreciably greater than for the pure metal. This may be an indication that the temperature dependence of stacking fault energy and modulus is also different for the alloy, leading to the apparent scatter of data in the normalized presentation.

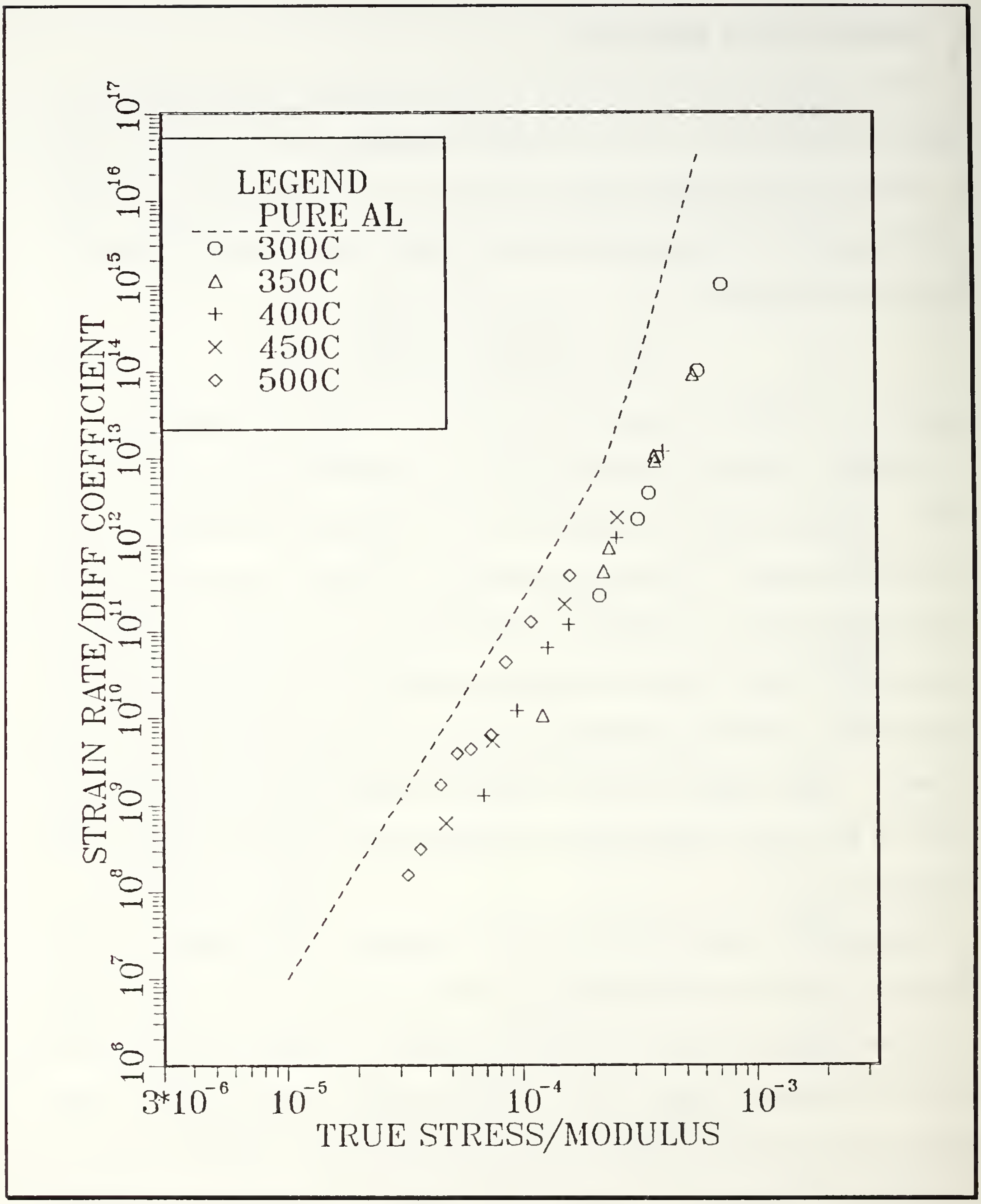

Figure 20. Al-2.0%Li $\dot{\varepsilon}$ /D vs. σ/E as Compared to Pure Al

I. INTERPRETATION OF RESULTS

First, the stress dependence of creep for the alloy is the same as that for pure Al. Second, the observation of sub-grain formation following the extensive primary stages of creep is also identical to the creep mechanisms of the pure metal. Third, the activation energy clearly exhibits a notably different temperature dependence than does the activation energy for pure Al. The activation energy may be considered a summation of self-diffusion, stacking fault energy and modulus components (equation 10). As noted earlier in Chapter II, the addition of Li to Al has the effect of increasing the modulus due to the effect of Li on bonding in the ordered structure. If the alloy were to undergo an order/disorder transition, e.g. in the temperature range between 400°C and 500°C, this could result in a more rapid decrease in modulus than for the pure metal and could account for the values of Q_c being greater than those for self-diffusion in this temperature regime.

While the creep characteristics of Al-2.0%Li resemble those of Al, there is strengthening due to the Li addition and the magnitude of the strengthening increases as temperature decreases. Possible factors to account for this are listed below.

1. Activation Energy for Diffusion

First, there may be a direct effect on the diffusion activation energy, that is, the rate at which atoms jump into and exchange with vacancies in the alloy. The determined activation energy for Al^{26} diffusion in Al is 34 kcal/mole [Ref. 13]. However, most of the values for the activation energy for impurity diffusion in Al are found in the range of 28 to 32 kcal/mole [Ref. 13]. In 8090 and 8091 the diffusivity of Li at 500°C is 2.5 x 10^{-9} cm^2/sec, while that of Al is

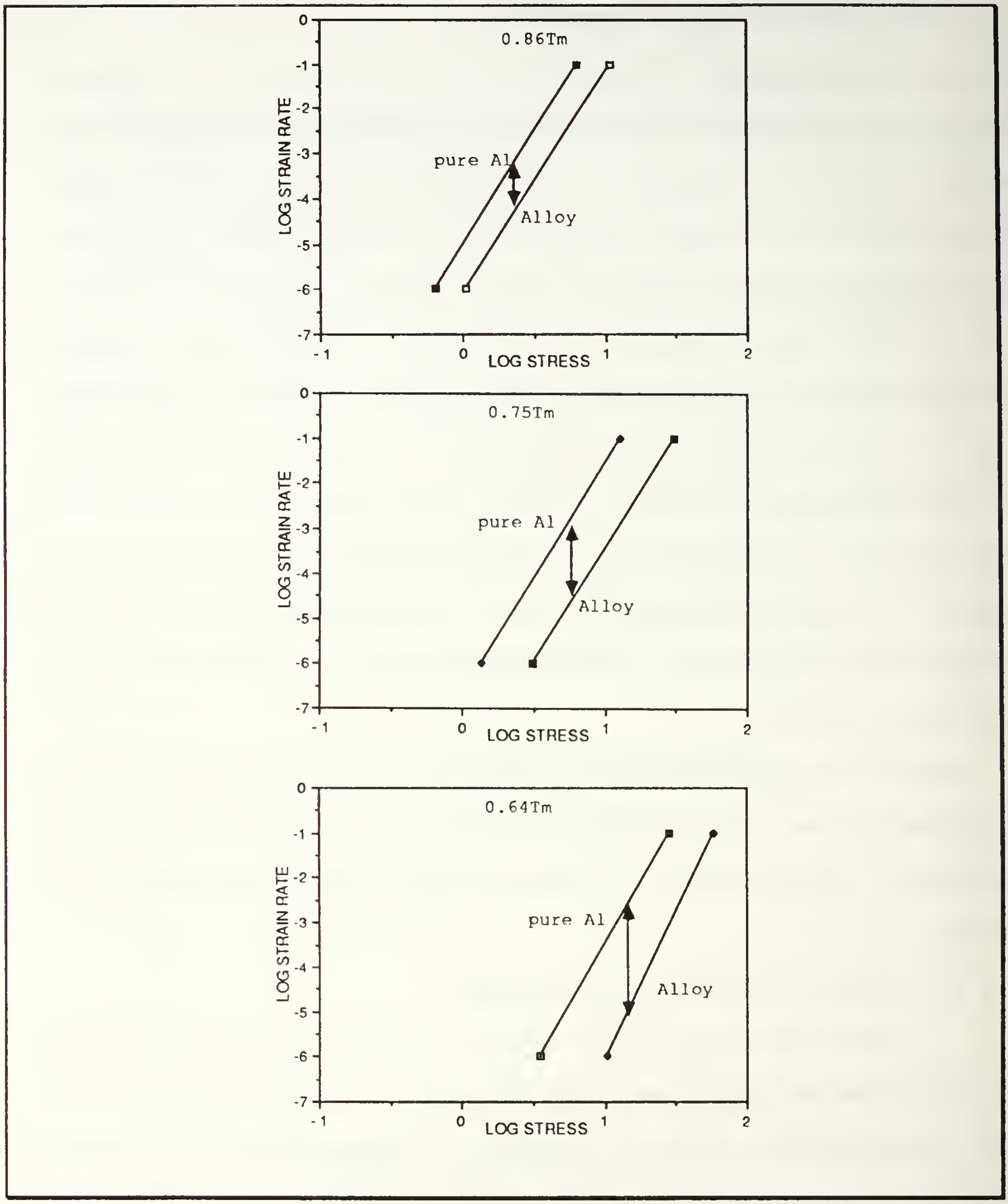

Figure 21. Al-2.0%Li Log $\dot{\varepsilon}$ vs. Log σ as Compared to Pure Al: 0.86T_m, 0.75T_m, 0.64T_m

3.9×10^{-10} cm^2/sec [Ref. 14]. These data suggest that the diffusion activation energy for Li in Al is not appreciably different at this temperature.

According to equation 7, the higher activation energy becomes, then the slower $\dot{\varepsilon}$ becomes. The present creep data on Al-2.0%Li indicate that Qc for the alloy is significantly higher than Qc for the pure metal from 300 to 450°C (47.4 to 54.9 kcal/mole) and then approaches that for Al from 470 to 500°C (40.4 to 33.1 kcal/mole). This explains, in part, why the creep rate of Al-2.0%Li at constant stress and the same homologous temperature is slower than that of the metal.

2. Modulus of Elasticity

In a random solid solution, there is little effect on bonding within the range of the solid solution. Most solid solutions do not show a strong influence on modulus of elasticity with alloy content, since the modulus reflects the way in which the average pair of atoms bond. If, on the other hand, there is an effect directly on the bonding between atoms, as could be reflected in an ordering reaction, causing an increased concentration of Li in the ordered region, an appreciable effect on the modulus of elasticity may be seen.

By equation 7, $\dot{\varepsilon}$ is proportional to the modulus-compensated stress, raised to the fifth power, $(\sigma/E)^5$. It is known that the room temperature modulus of elasticity for the alloy is higher than that for pure Al. Each wt.pct. of Li added to Al increases the modulus by 6%, and at room temperature the alloy's modulus of elasticity is reported to be 78.5 GPa [Ref. 15]. By considering the increase in modulus, as a result of the presence of the 2.0% Li in the alloy, then for constant stress, the $\dot{\varepsilon}$ of Al-2.0%Li would be slower than that of Al.

It is also known that for any pure metal or simple alloy that the modulus of elasticity, overall, decreases with temperature. It is postulated, based on the work of Fox and Fisher[Ref. 2] and on the work of Radmilovic *et al* [Ref. 3], that within the range of the solid solution, there is a tendency of the Li to form an ordered structure. Thus, the modulus of elasticity may exhibit a more rapid decrease with increasing temperature than does the modulus of pure Al at temperatures below, but near, the ordering temperature (expected to be ~700K based on the data of this research).

If it is assumed that this apparent increase in activation energy is associated with the modulus of elasticity alone, then it is postulated that the elastic modulus as a function of temperature for the alloy, might appear as shown in Figure 22. On this figure, the data for the modulus of pure Al is shown by the solid line. The data for the modulus of the alloy is available at room temperature (300K) and is 78.5 GPa [Ref. 15]. The modulus of the alloy at the melting point was calculated using the following relationship [Ref. 2]:

$$E = K\mu\theta^2 \qquad (12)$$

where K is a physical constant, μ is the average mass of the alloy and θ is the Debye temperature. The temperature at the melting point of the alloy is 901K and the calculated modulus of elasticity is 37 GPa. The observed effect upon the activation energy would arise if the alloy's modulus were to decrease with temperature as shown by the dashed line. In the temperature interval of 600 to 720K, the alloy has a steeper, more negative slope as a result of disorder through heating, or conversely, ordering upon cooling. The slope associated with the triangle represents a variation of modulus with temperature sufficient to account

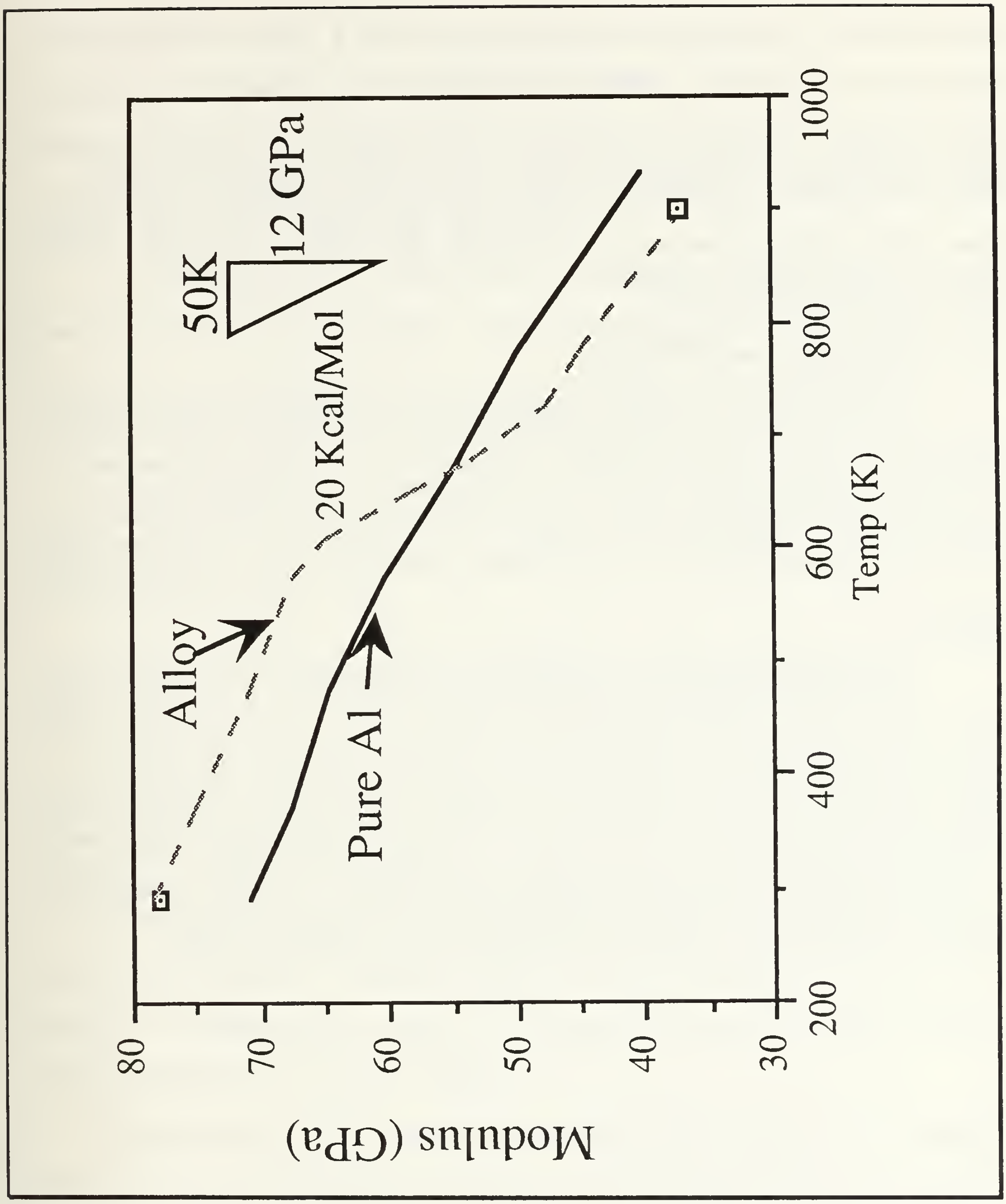

Figure 22. Proposed Modulus of Elasticity as a Function of Temperature

for an increase in the creep activation energy from a value of 34 kcal/mole (associated with diffusion only), to a value of 55 kcal/mole (as observed experimentally). This slope was calculated using equation 10. Without using the Debye temperature, the proposed modulus of the alloy is expected to decrease to values below the modulus of pure Al because the melting temperature of the alloy is less than for the metal.

3. Stacking Fault Energy

It was shown in Chapter II that under the condition of climb control, the creep rate is described by equation 7 and that the creep rate is proportional to the cube of the stacking fault energy, $(\gamma)^3$. This suggests that if the γ of the alloy is lower than that of Al then, at constant stress, the creep rate will be slower than that of Al.

The ordering reaction could also have an influence on the stacking fault energy. In the case of pure Al, the best evidence is that, essentially, there is no effect of temperature on stacking fault energy. The effect of Li upon the stacking fault energy of Al is not known It is acknowledged that in the search for accurate physical models, the stacking fault energy is a difficult quantity to measure, and there are no data in the literature that are widely accepted.

V. CONCLUSIONS

The following conclusions can be drawn concerning the behavior and characteristics of the binary alloy Al-2.0%Li:

1. Al-2.0%Li exhibits a creep response consisting of a pronounced primary, a secondary, and a tertiary phase. This characteristic curve shape is similar to that for pure Al and demonstrates that the steady-state creep behavior of the class II Al-2.0%Li alloy (metal class) is controlled by some form of dislocation climb.

2. Considering the stress dependence of each corresponding strain rate, the stress exponent, n, varies from ~6.7 at 300°C to ~4.9 at 500°C, and is similar to that reported for Al (n ~ 5).

3. Al-2.0%Li data at 500°C correspond to within a factor of 2 to data reported by Park *et al* for a similar alloy using double shear creep testing.

4. Activation energy obtained for Al-2.0%Li from isothermal creep and from temperature cycling testing indicates an anomously high activation energy from 300°C to 450°C. Activation energy for creep reaches a maximum value of 55 kcal/mole, a difference of about 20kcal/mole higher than that for Al at a temperature of 400°C. This may result from the temperature-dependence of modulus or stacking fault energy or through additional processes such as ordering of the Li in the solid solution.

5. For the same homologous temperature the creep strength of Al-2.0%Li is higher than that of Al; a possible decrease in the stacking fault energy combined with a measured increase in the activation energy for creep in Al with the addition of Li may responsible for this finding.

VI. RECOMENDATIONS

1. Investigate alternative methods to assess the order/disorder reaction.
2. Determine modulus as a function of temperature using ultrasonic vibration methods.
3. Investigate microstructure with Transmission Electron Microscopy (TEM).
4. Investigate the effects of various elements in an Al-Li-X.

APPENDIX A. STRESS STRAIN CURVES

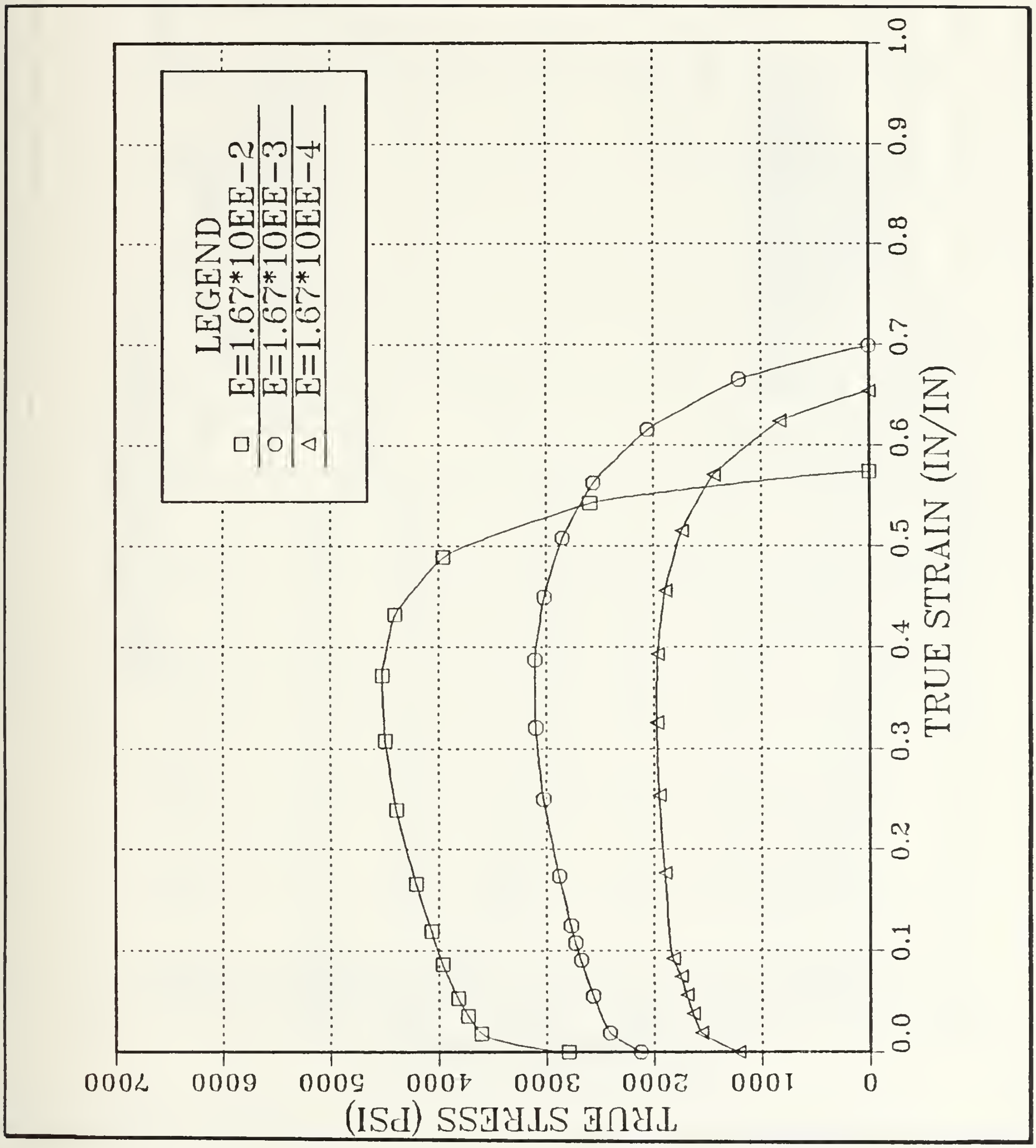

Figure 22. Stress Strain Curves at 350°C for Various Strain Rates

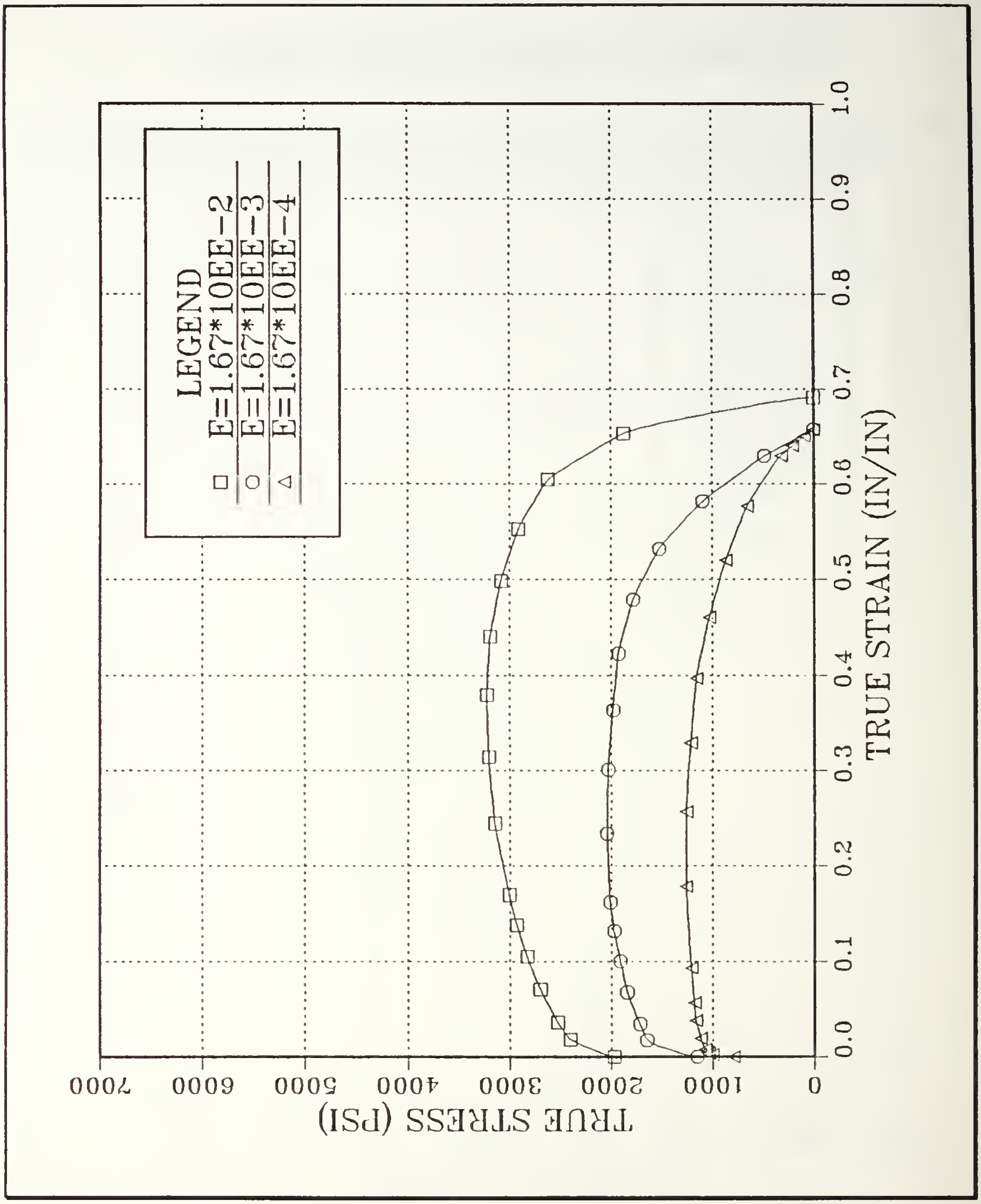

Figure 23. Stress Strain Curves at 400°C for Various Strain Rates

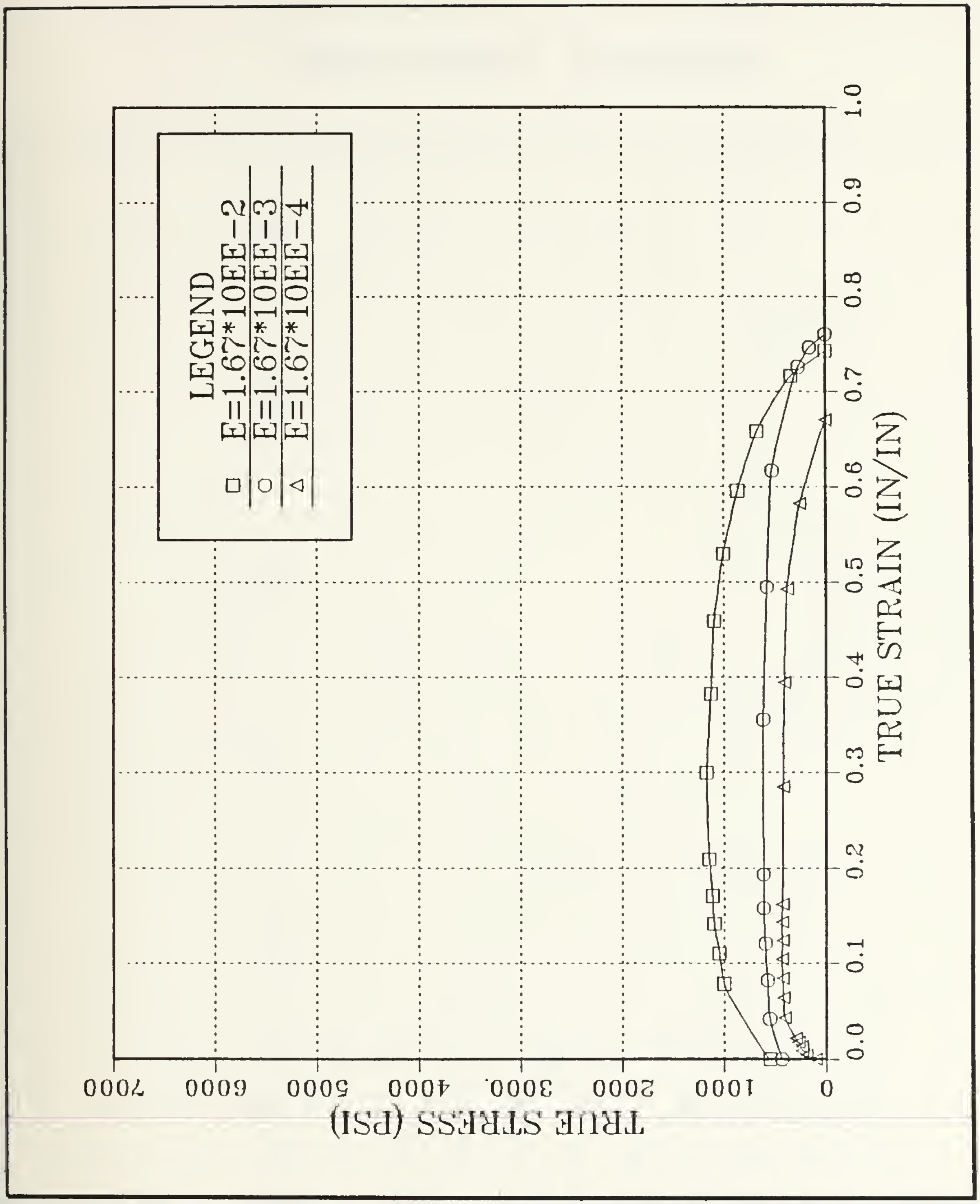

Figure 24. Stress Strain Curves at 500°C for Various Strain Rates

APPENDIX B. CREEP CURVES

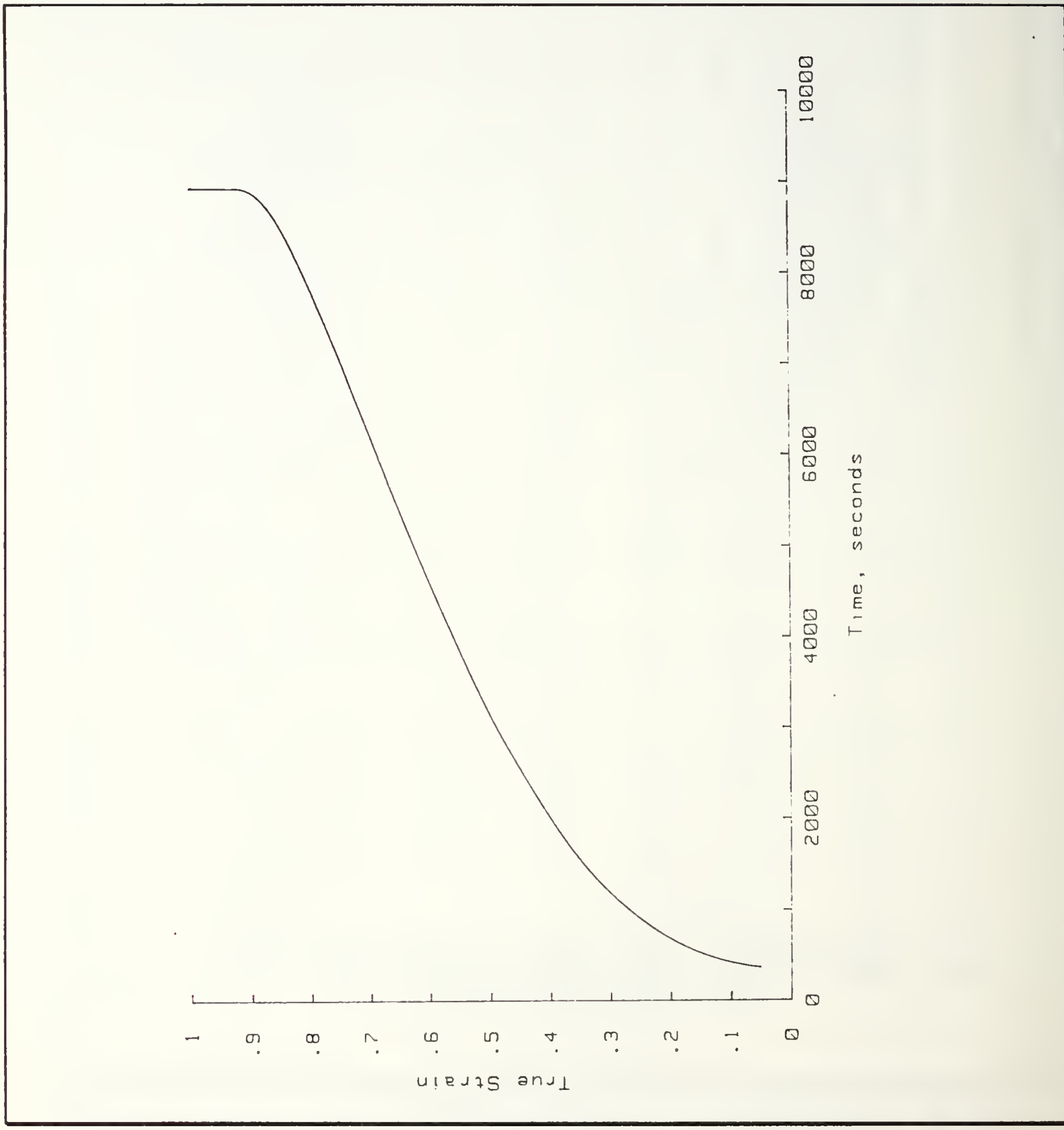

Figure 25. Creep Curve at 300°C for a Stress of 21.2 MPa:

$\dot{\varepsilon}_{min} = 6.40 \times 10^{-5}$ sec^{-1}

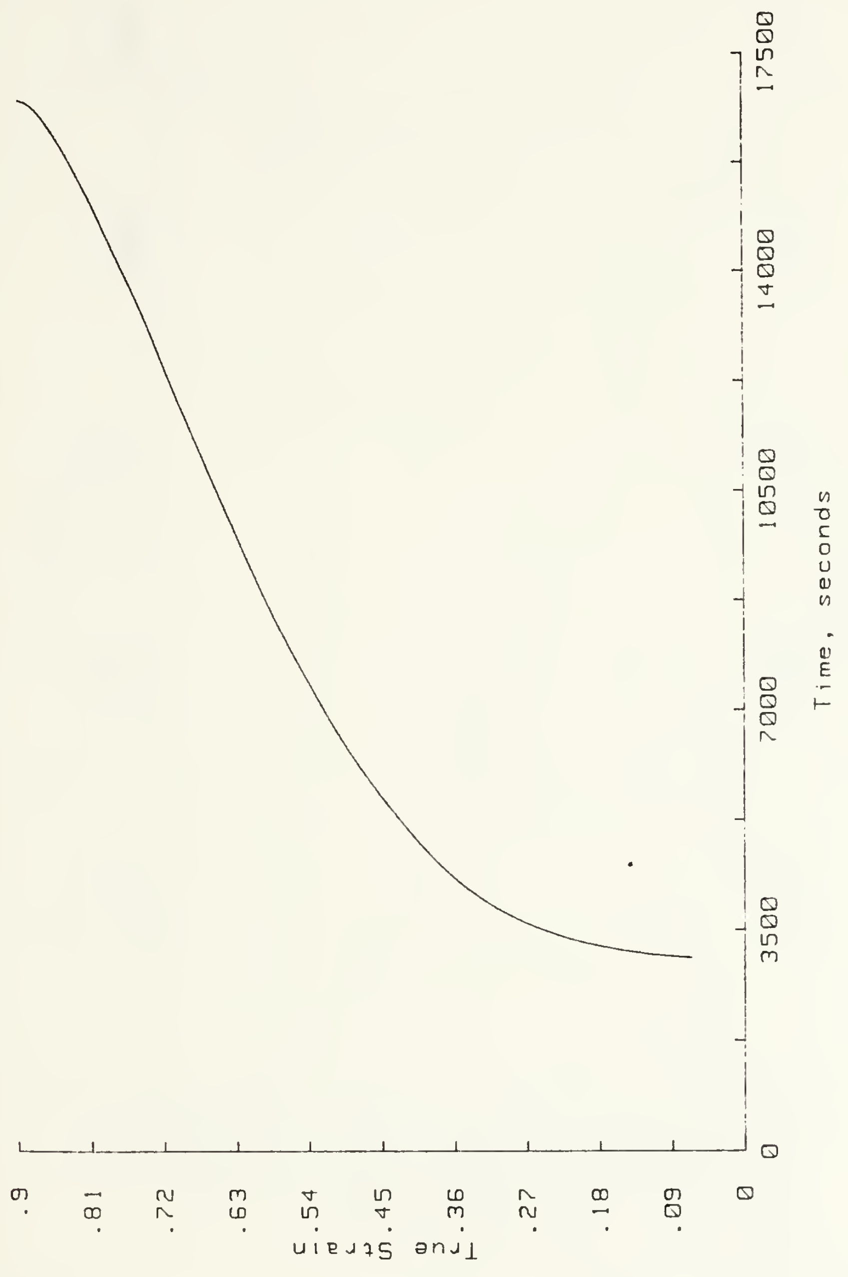

Figure 26. Creep Curve at 300^{o}C for a Stress of 19.0 MPa:

$\dot{\varepsilon}_{min}$ = 3.25 x 10^{-5} sec^{-1}

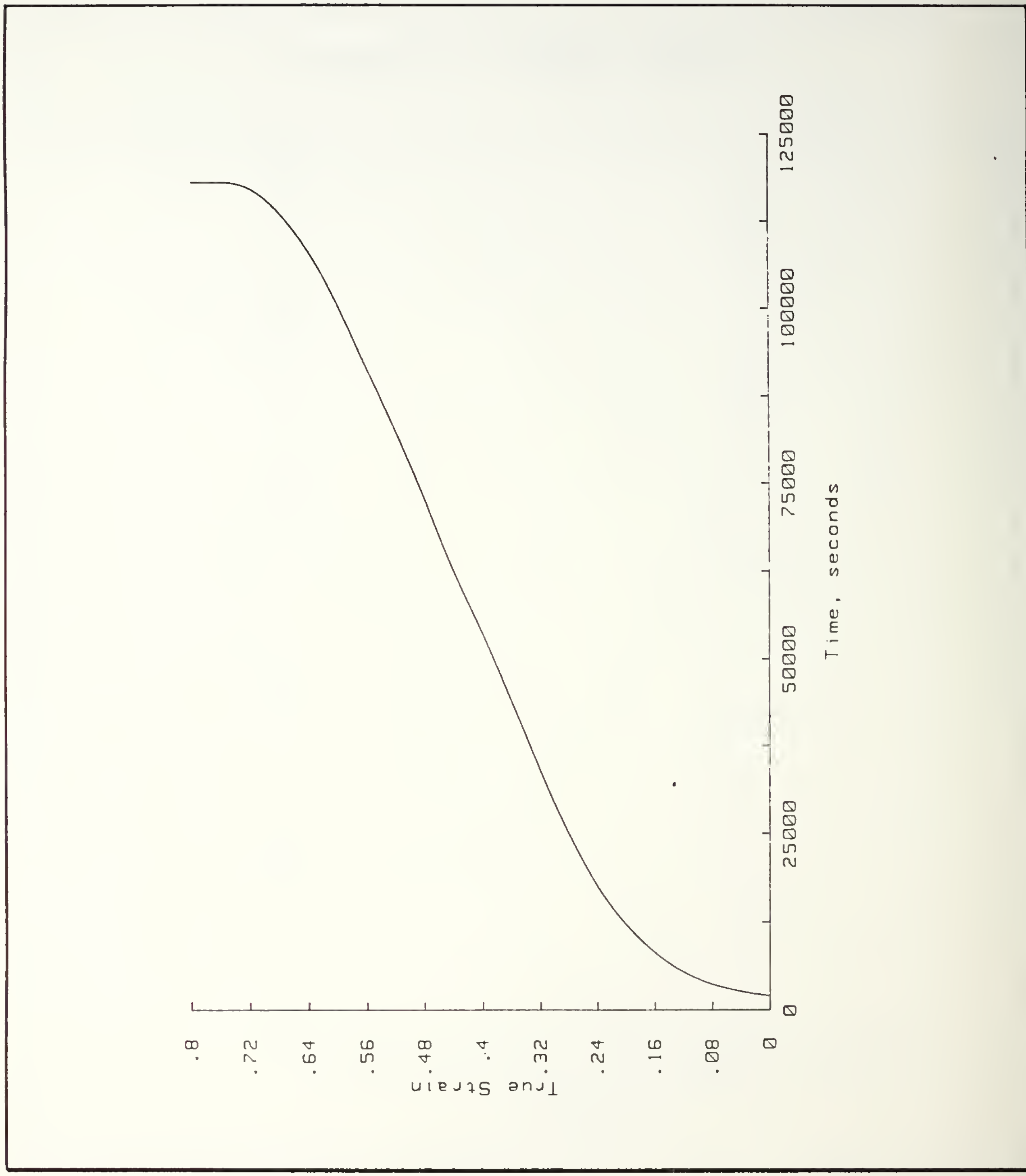

Figure 27. Creep Curve at 300°C for a Stress of 13.0 MPa:

$\dot{\varepsilon}_{min}$ = 4.24 x 10^{-6} sec^{-1}

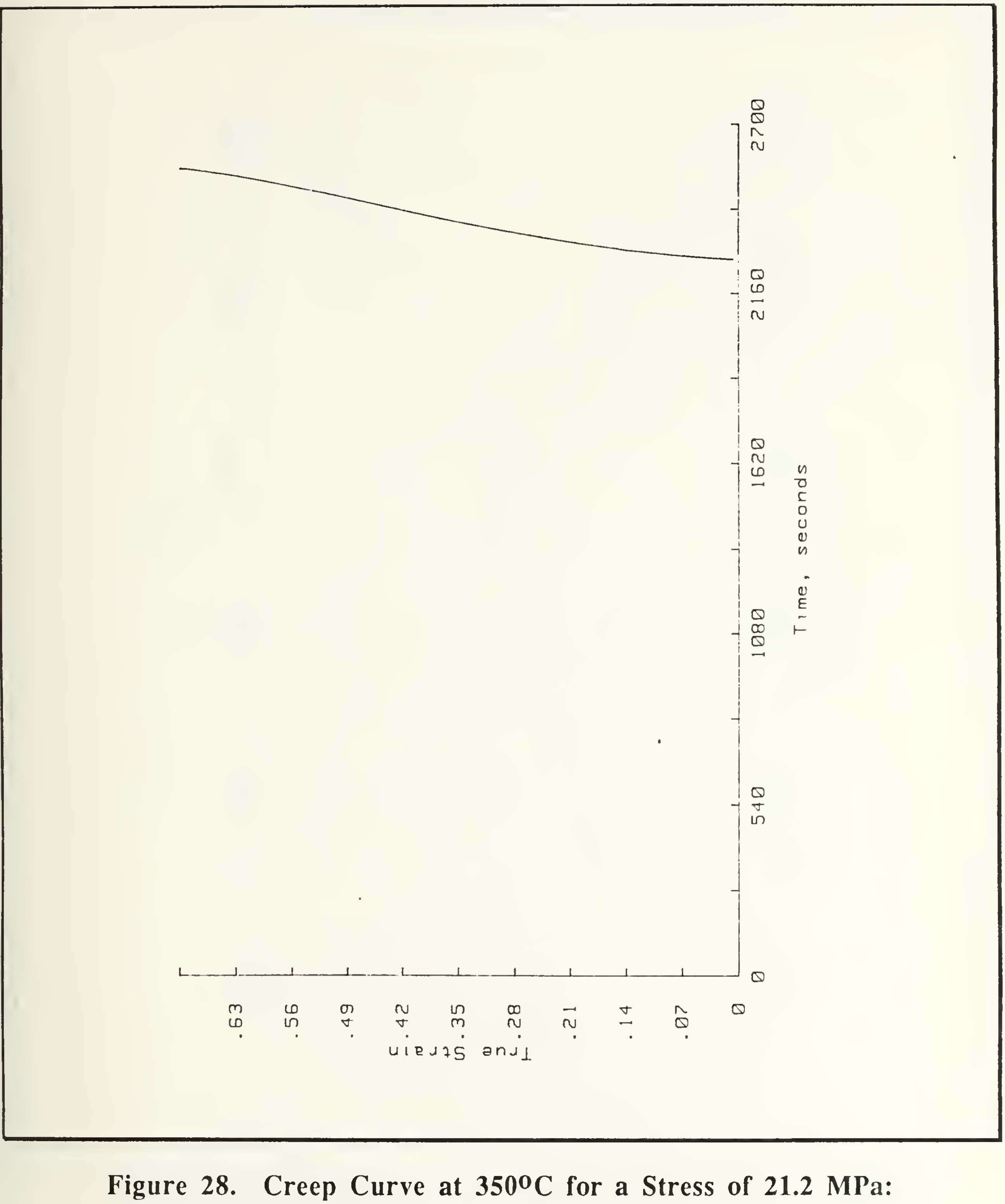

Figure 28. Creep Curve at 350°C for a Stress of 21.2 MPa:

$$\dot{\varepsilon}_{min} = 1.90 \times 10^{-3} \ sec^{-1}$$

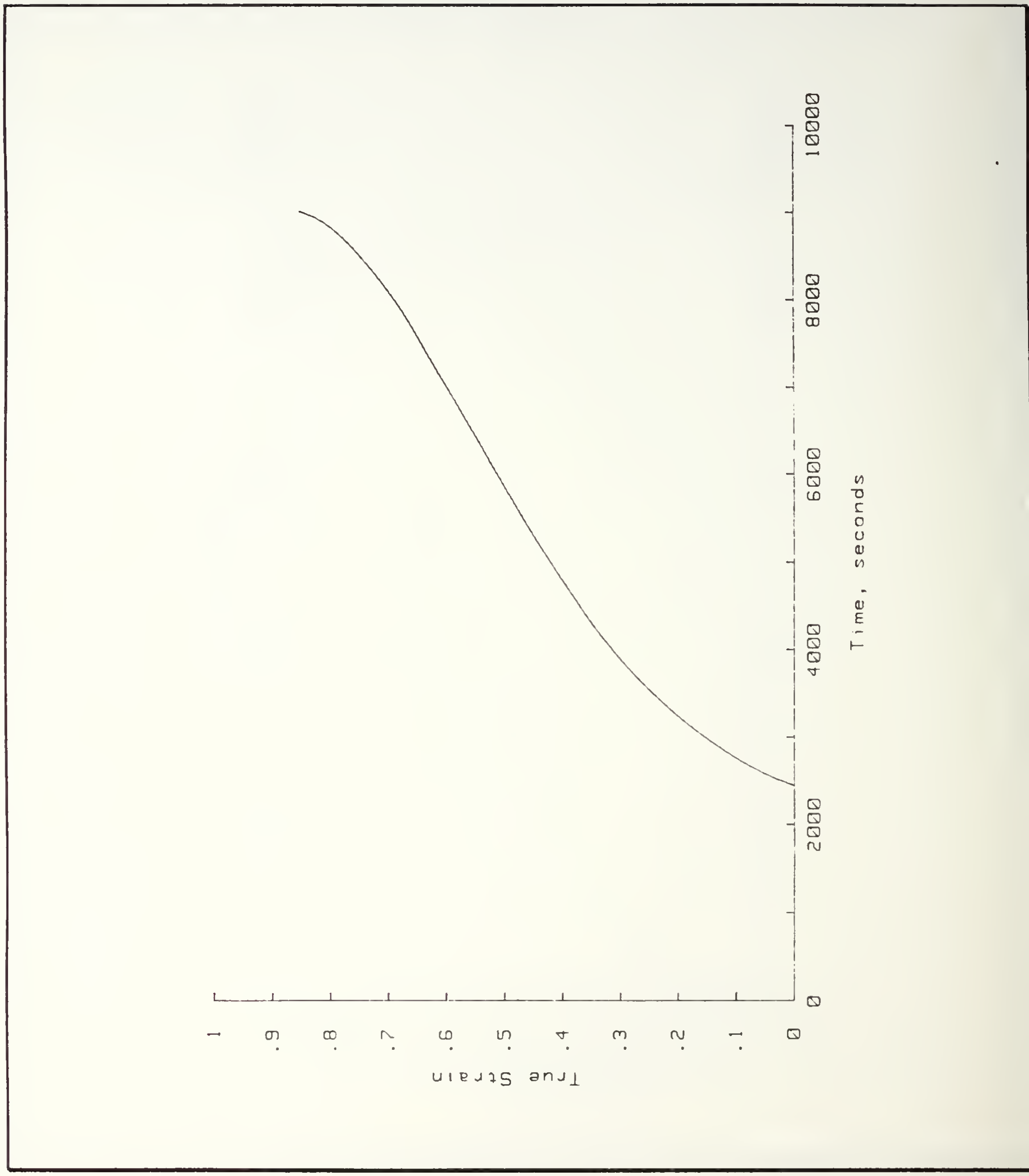

Figure 29. Creep Curve at 350°C for a Stress of 12.9 MPa:

$\dot{\varepsilon}_{min} = 8.88 \times 10^{-5}\ sec^{-1}$

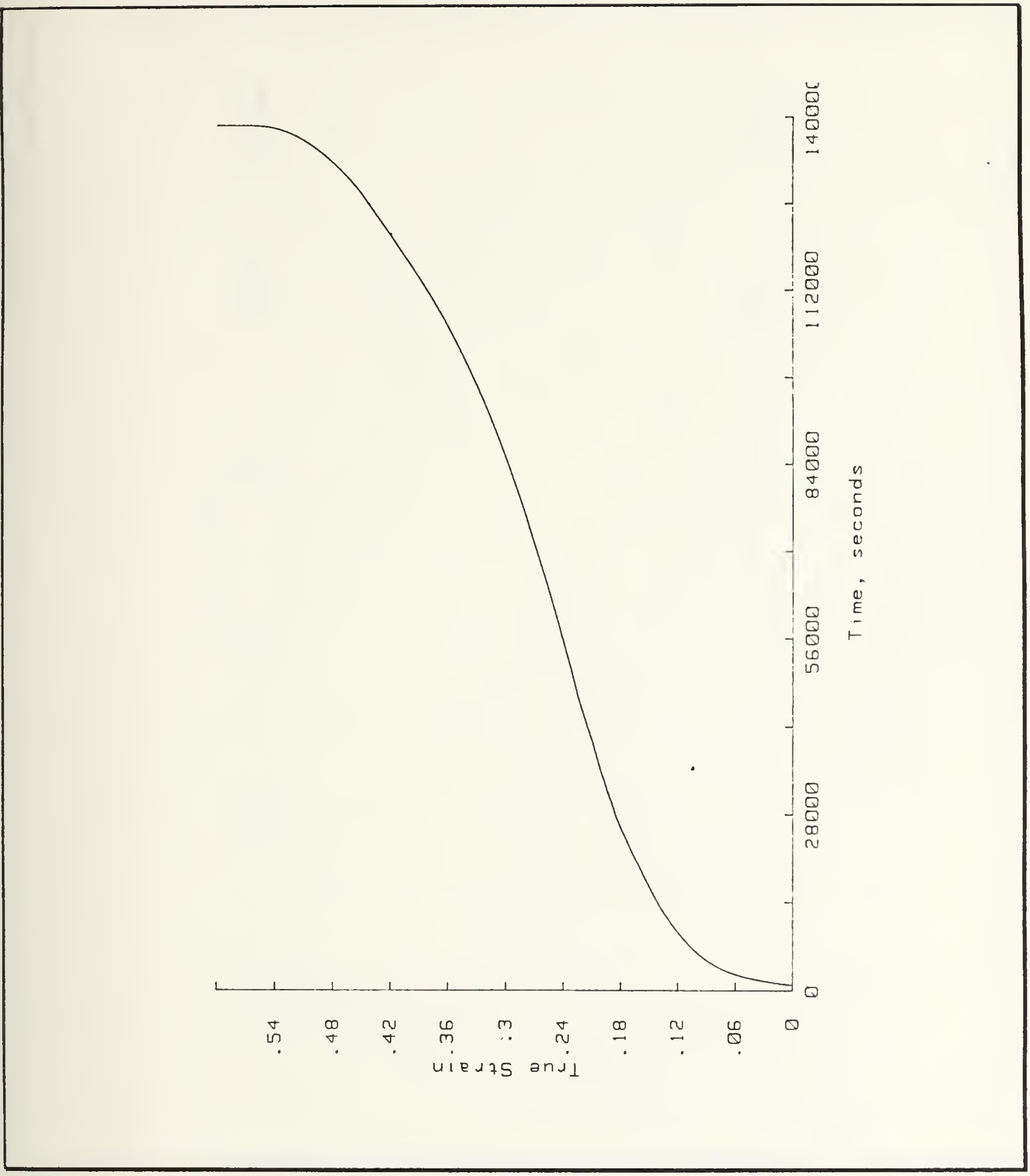

Figure 30. Creep Curve at 350°C for a Stress of 7.00 MPa:

$\dot{\varepsilon}_{min} = 1.93 \times 10^{-6}\ sec^{-1}$

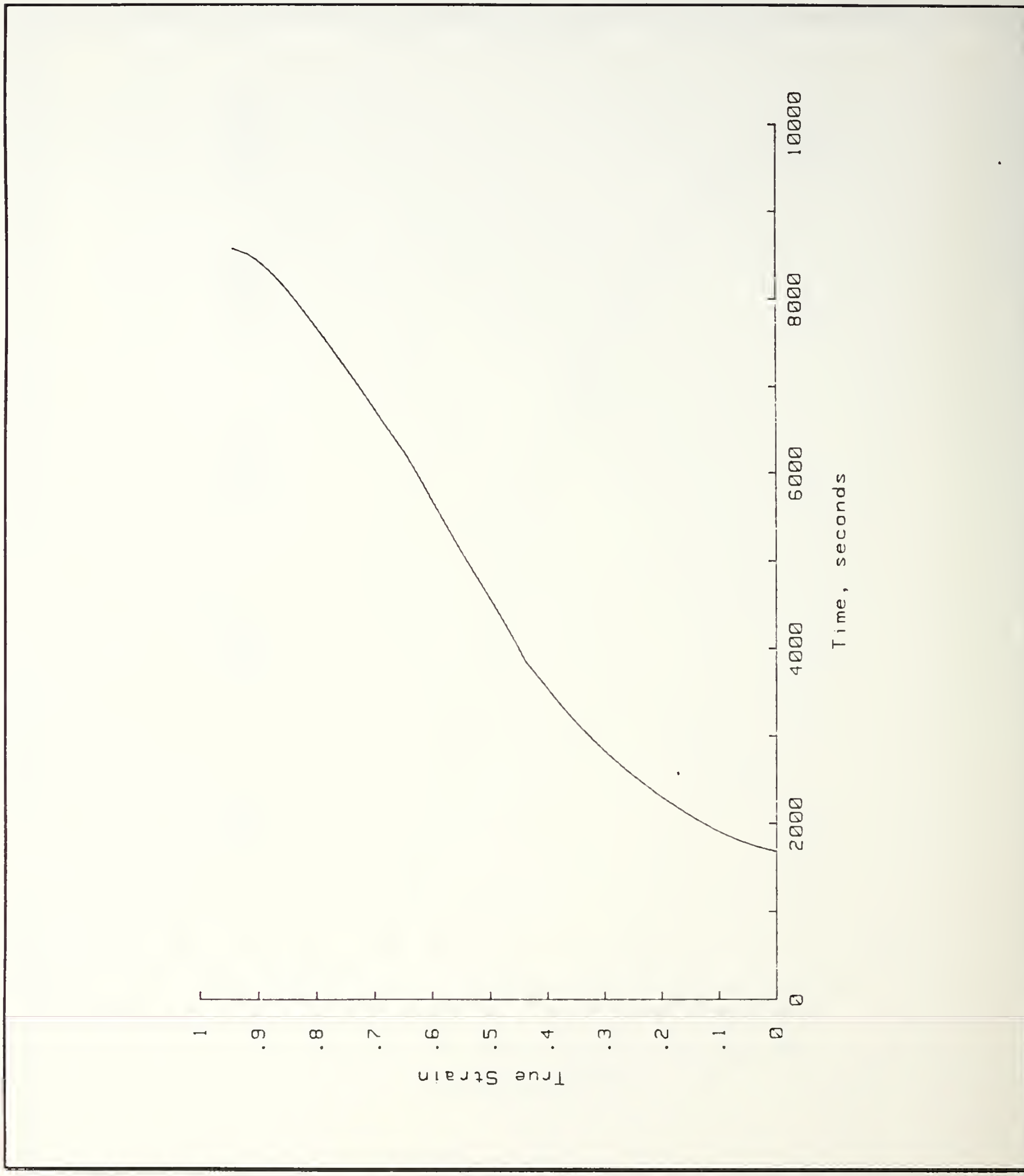

Figure 31. Creep Curve at 400°C for a Stress of 7.10 MPa:

$\dot{\varepsilon}_{min} = 9.00 \times 10^{-5}\ sec^{-1}$

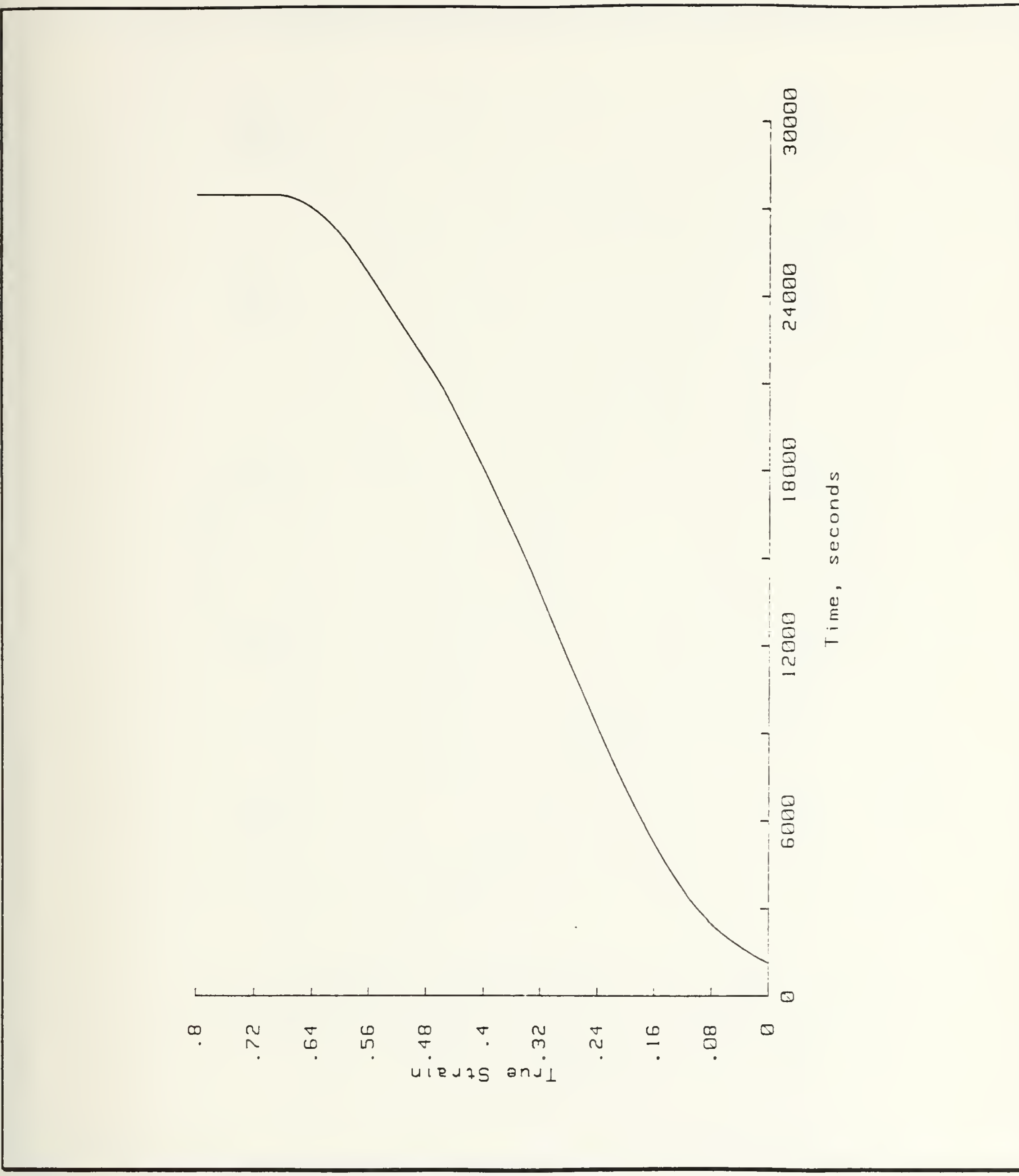

Figure 32. Creep Curve at 400°C for a Stress of 5.27 MPa:

$\dot{\varepsilon}_{min} = 1.71 \times 10^{-5}\ sec^{-1}$

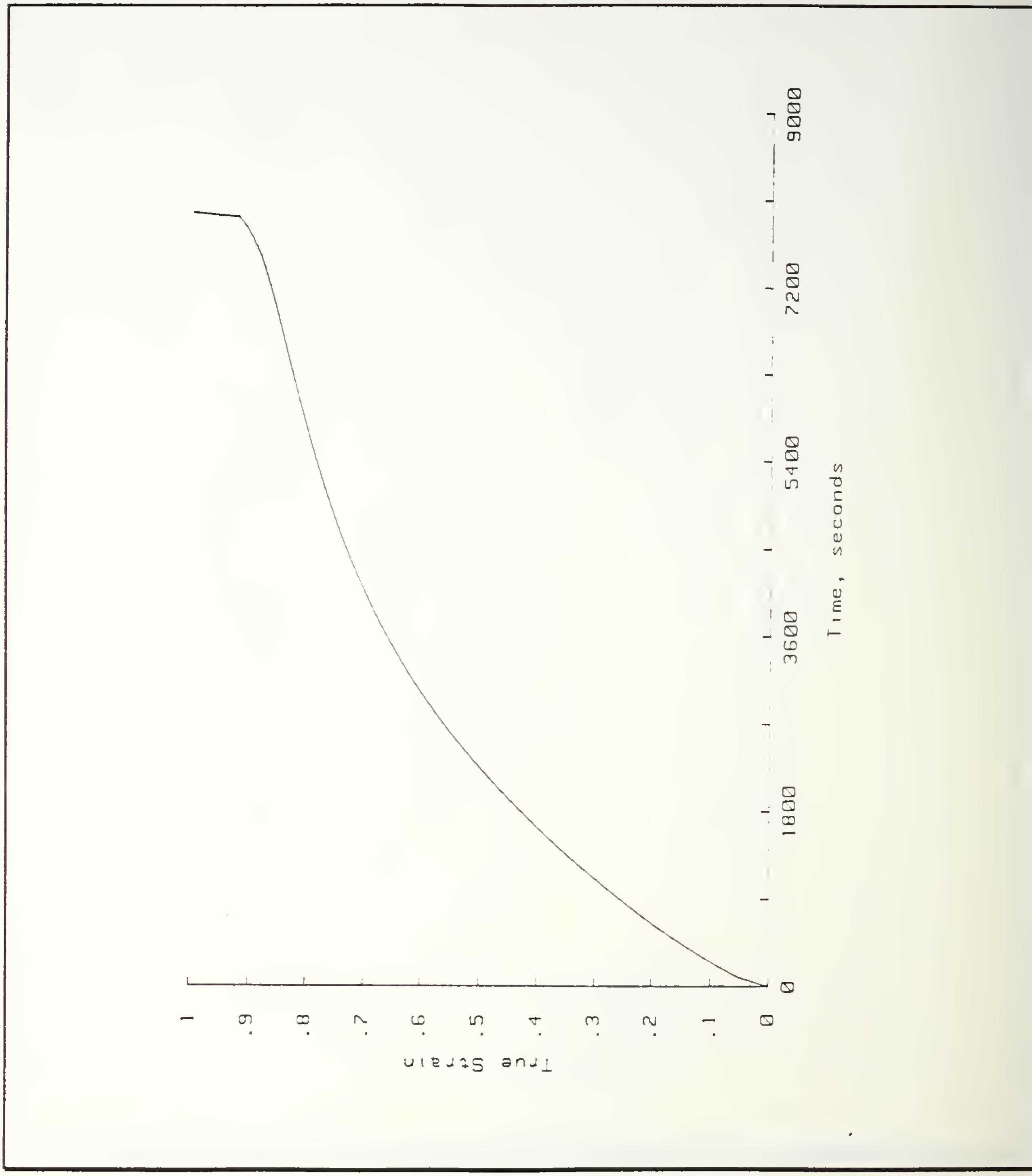

Figure 33. Creep Curve at 450°C for a Stress of 2.35 MPa:

$\dot{\varepsilon}_{min} = 4.43 \times 10^{-5}\ sec^{-1}$

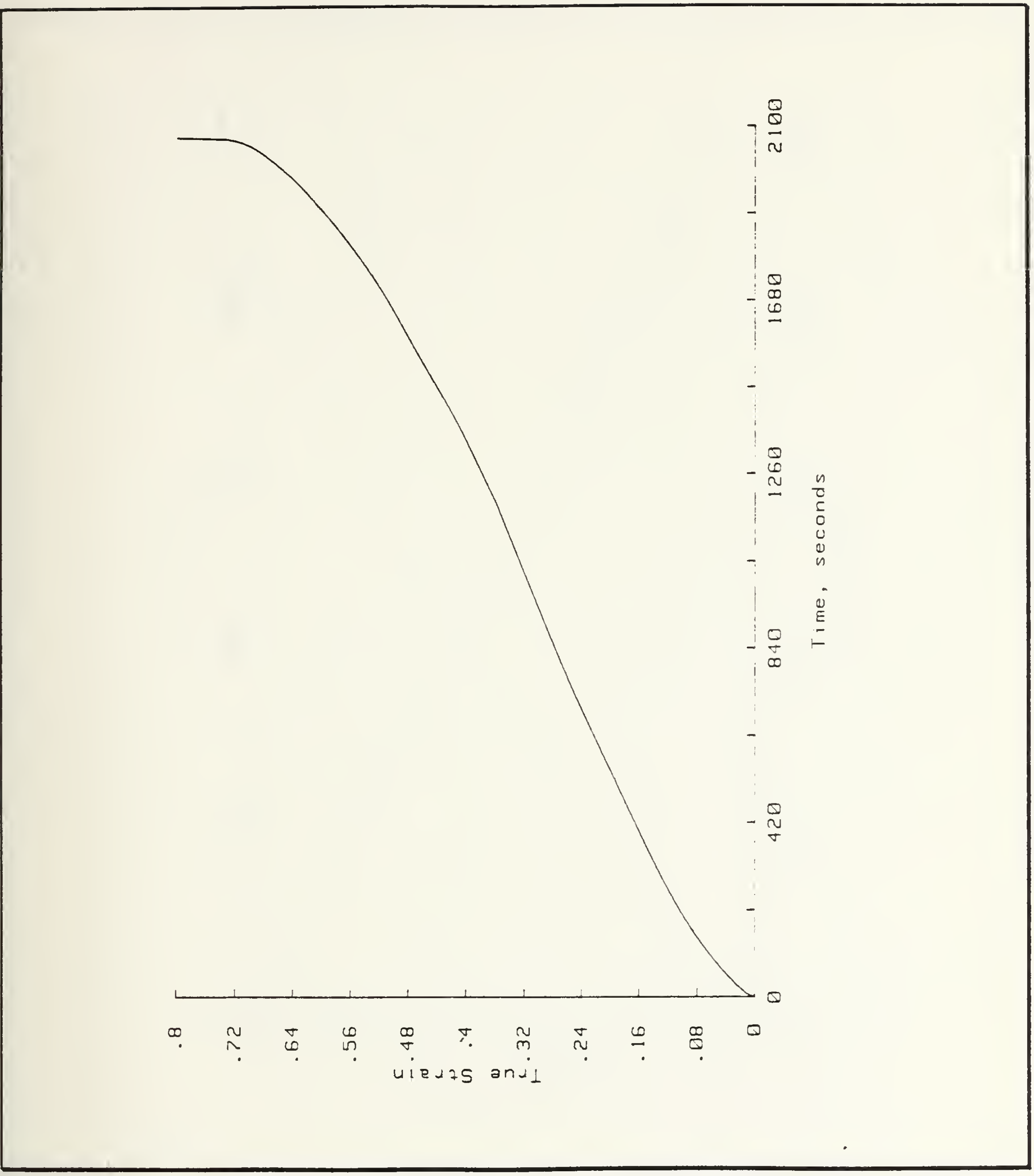

Figure 34. Creep Curve at 500°C for a Stress of 3.02 MPa:

$\dot{\varepsilon}_{min} = 2.43 \times 10^{-4}\ sec^{-1}$

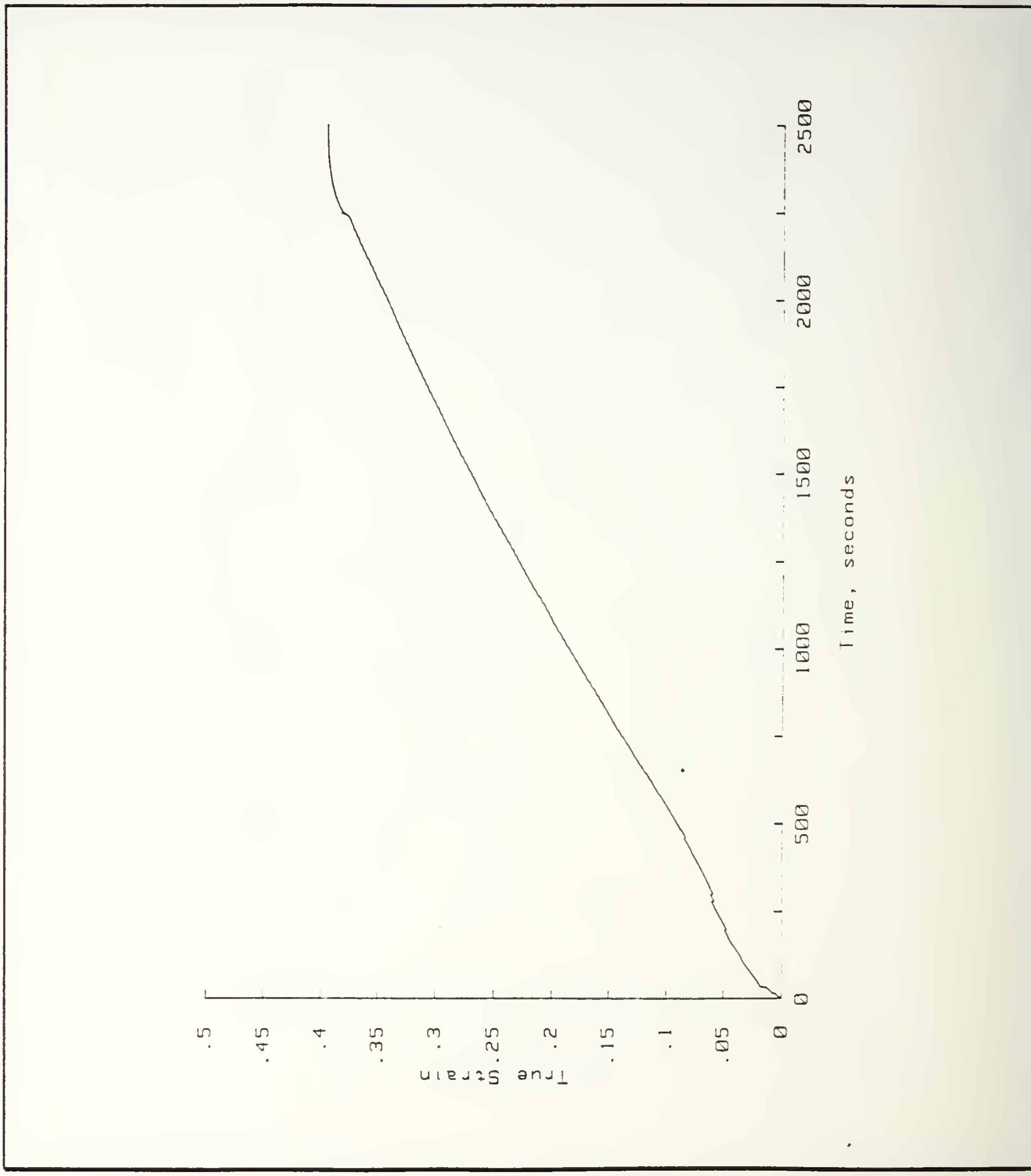

Figure 35. Creep Curve at 500^{o}C for a Stress of 2.65 MPa:

$\dot{\varepsilon}_{min}$ = 1.49 x 10^{-4} sec^{-1} (Arrested Test)

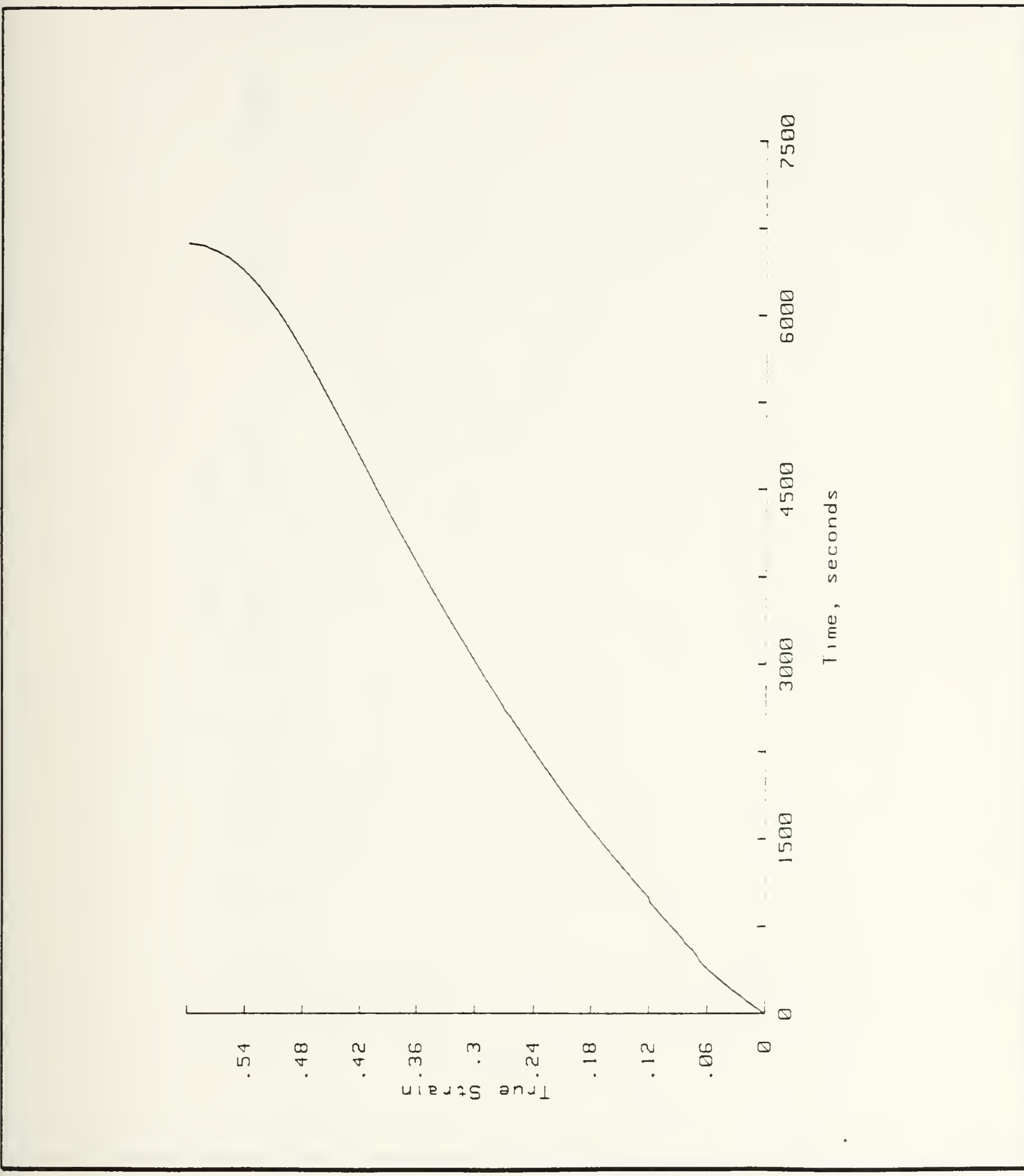

Figure 36. Creep Curve at 500°C for a Stress of 2.25 MPa:

$$\dot{\varepsilon}_{min} = 6.59 \times 10^{-5}\ sec^{-1}$$

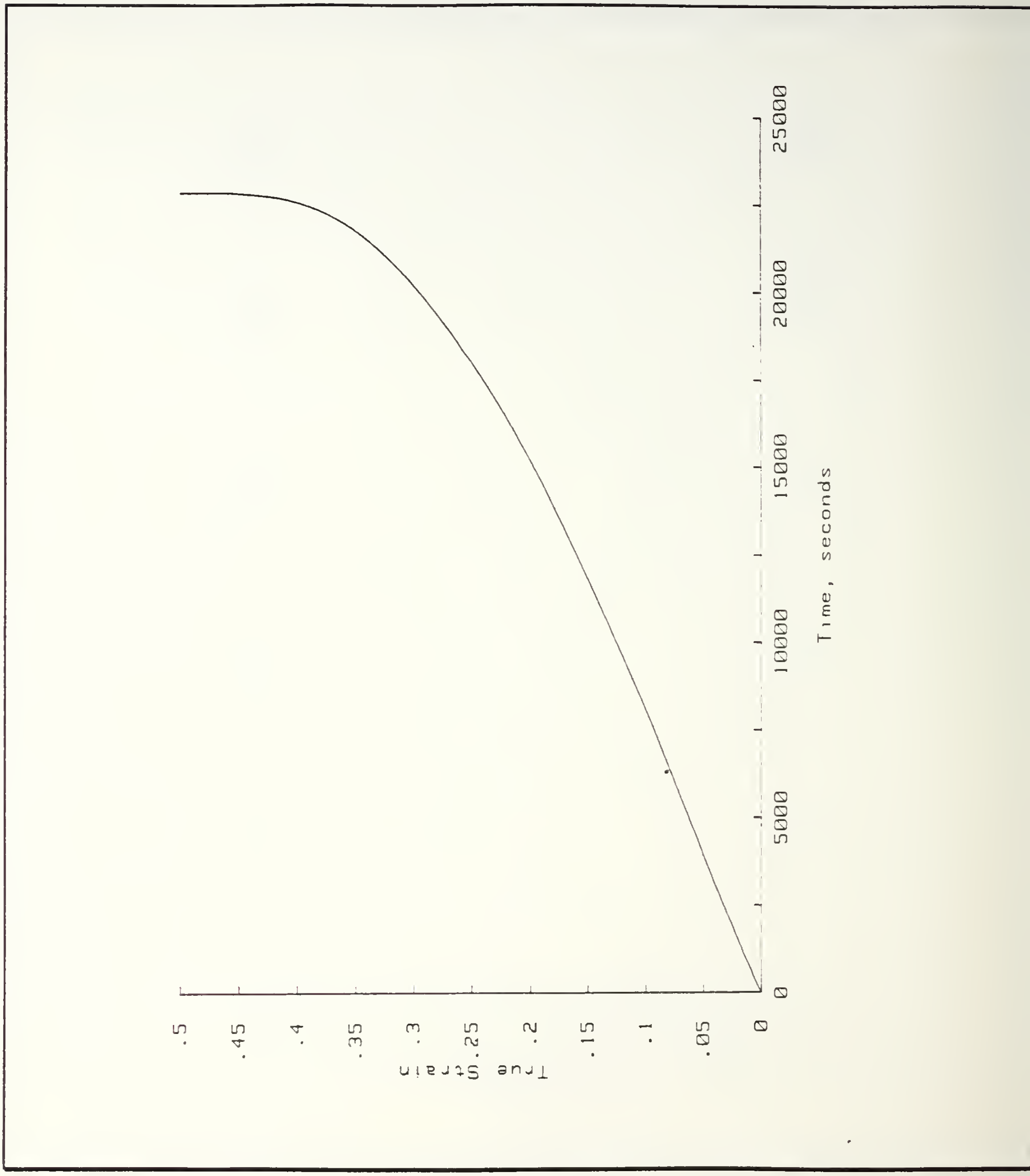

Figure 37. Creep Curve at 500°C for a Stress of 1.84 MPa:

$\dot{\varepsilon}_{min} = 1.20 \times 10^{-5}\ sec^{-1}$

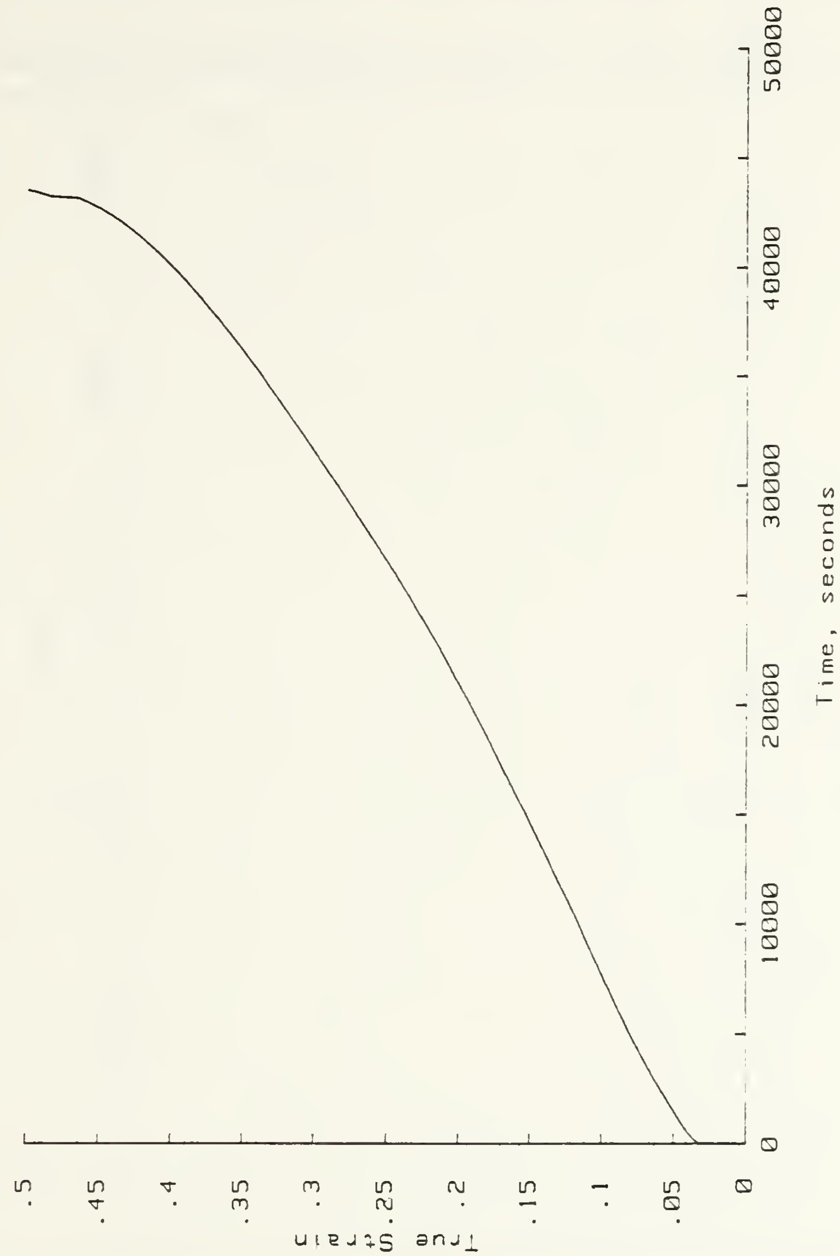

Figure 38. Creep Curve at 500^{o}C for a Stress of 1.63 MPa:

$\dot{\varepsilon}_{min} = 6.00 \times 10^{-6}$ sec^{-1}

APPENDIX C. TEMPERATURE CYCLING CREEP CURVES

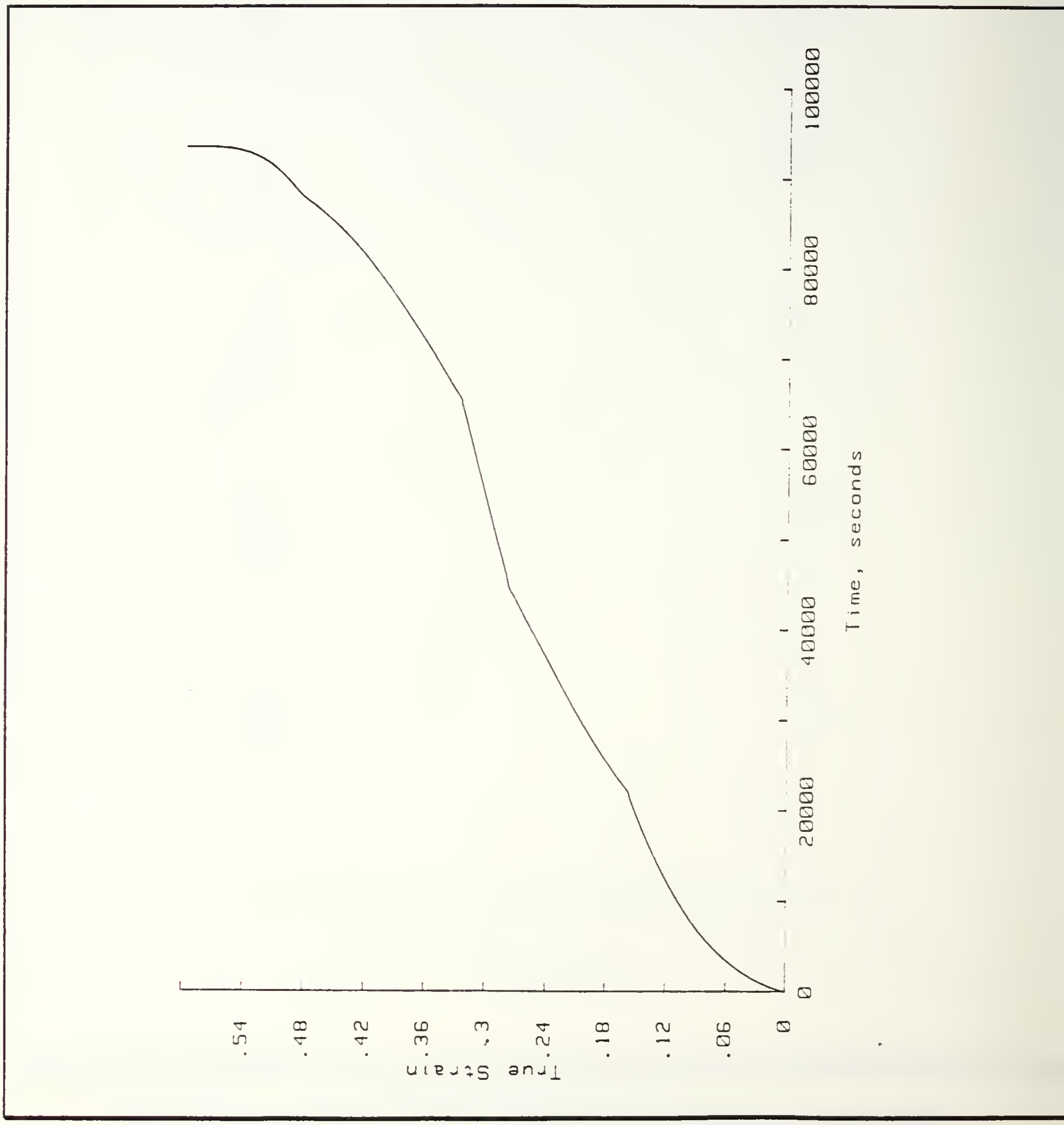

Figure 39. Creep Curve at 300-310°C for a Stress of 11.9 MPa:

$\dot{\varepsilon}_1 = 2.10 \times 10^{-6}\ sec^{-1}$ & $\dot{\varepsilon}_2 = 4.30 \times 10^{-6}\ sec^{-1}$

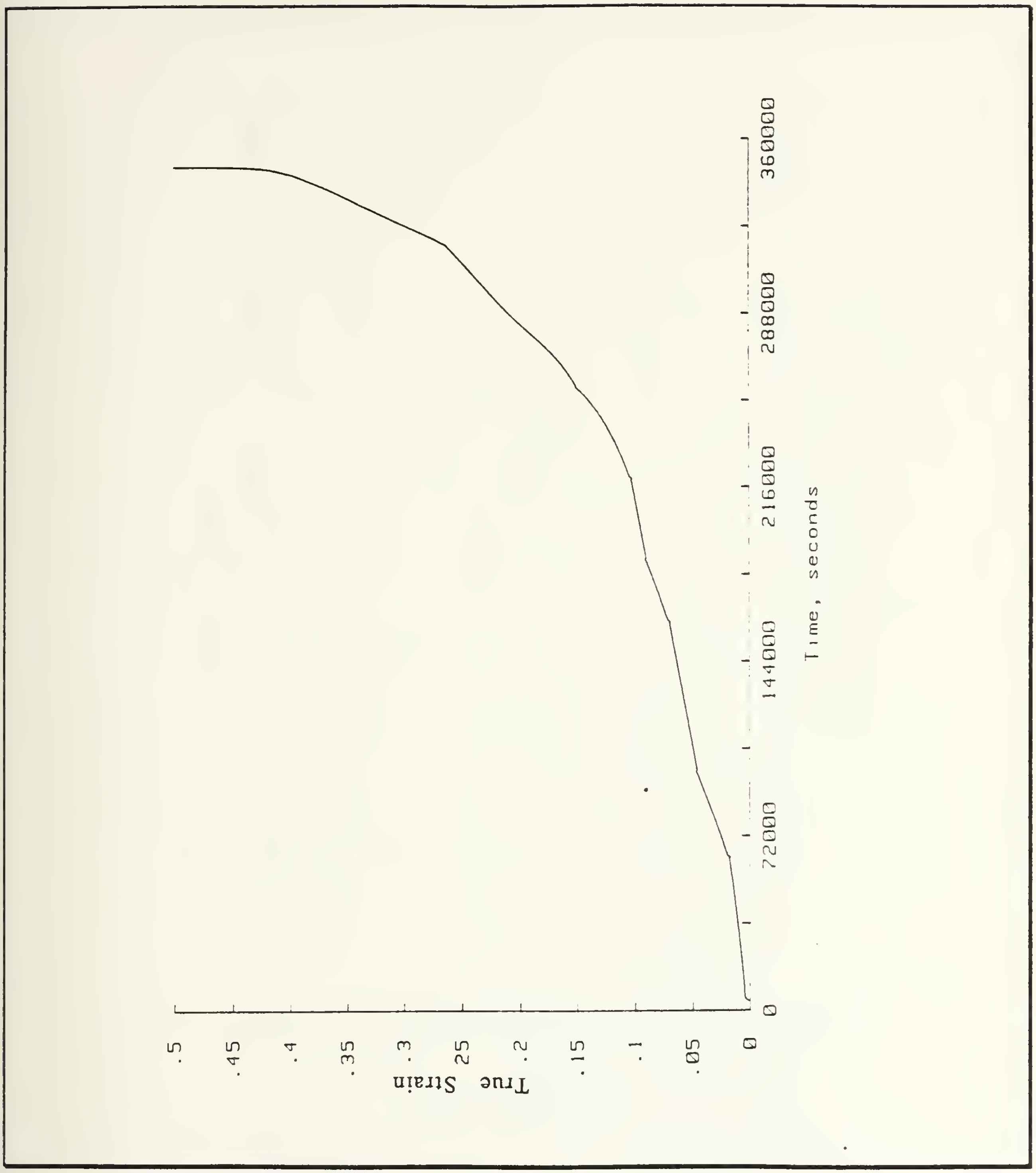

Figure 40. Creep Curve at 400-410^{o}C for a Stress of 3.03 MPa:

$\dot{\varepsilon}_1 = 3.98 \times 10^{-7}$ sec^{-1} & $\dot{\varepsilon}_2 = 7.31 \times 10^{-7}$ sec^{-1}

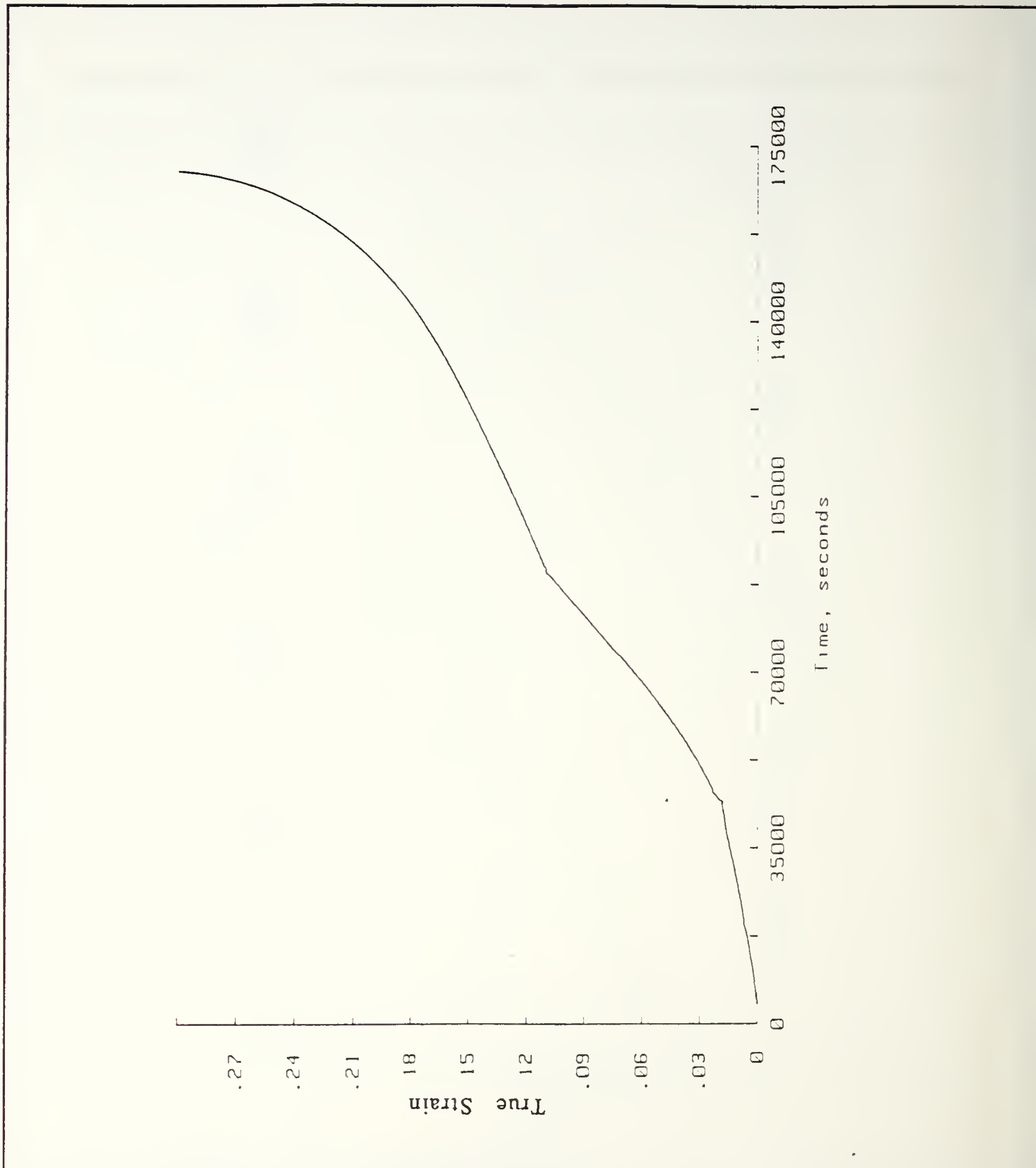

Figure 41. Creep Curve at 400-410°C for a Stress of 3.03 MPa:

$\dot{\varepsilon}_1 = 1.18 \times 10^{-6}\ \mathrm{sec}^{-1}$ & $\dot{\varepsilon}_2 = 2.22 \times 10^{-6}\ \mathrm{sec}^{-1}$

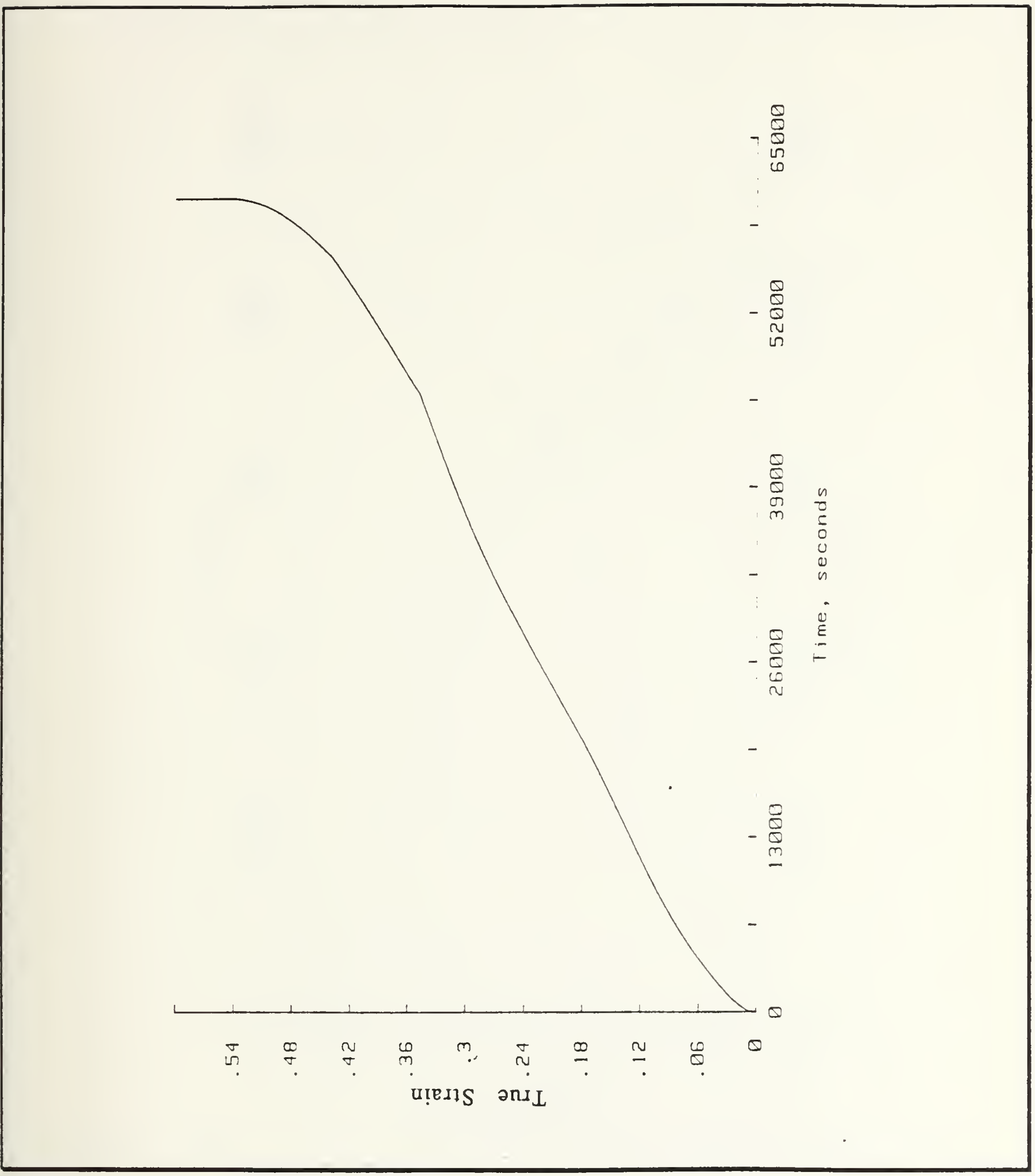

Figure 42. Creep Curve at 450-460^{o}C for a Stress of 2.46 MPa:

$\dot{\varepsilon}_1 = 5.15 \times 10^{-6}$ sec^{-1} & $\dot{\varepsilon}_2 = 8.69 \times 10^{-6}$ sec^{-1}

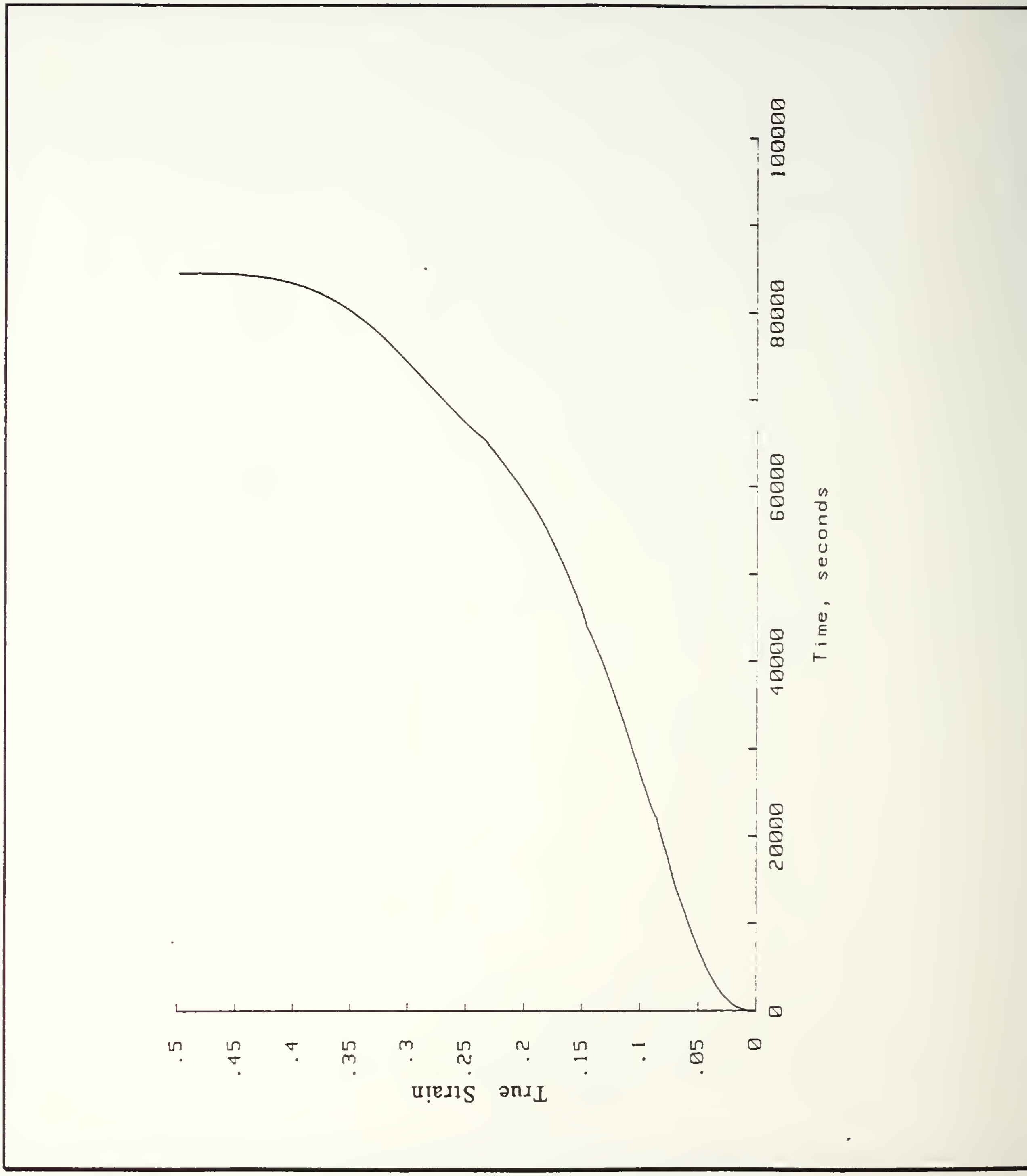

Figure 43. Creep Curve at 470-480^{o}C for a Stress of 2.03 MPa:

$\dot{\varepsilon}_1 = 1.75 \times 10^{-6}\ \text{sec}^{-1}$ & $\dot{\varepsilon}_2 = 2.52 \times 10^{-6}\ \text{sec}^{-1}$

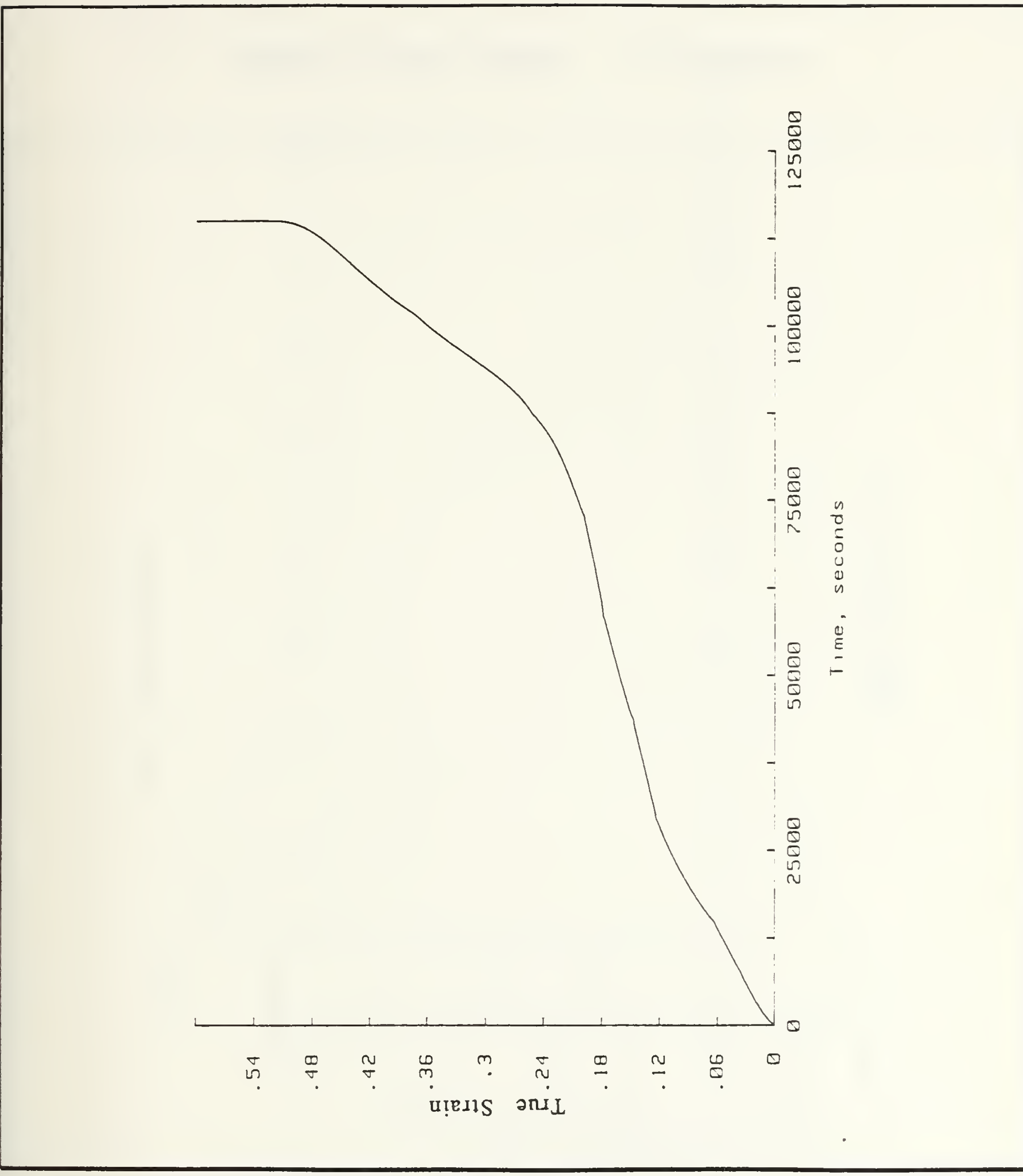

Figure 44. Creep Curve at 500-510^oC for a Stress of 1.64 MPa:

$\dot{\varepsilon}_1 = 1.51 \times 10^{-6}\ sec^{-1}$ & $\dot{\varepsilon}_2 = 1.99 \times 10^{-6}\ sec^{-1}$

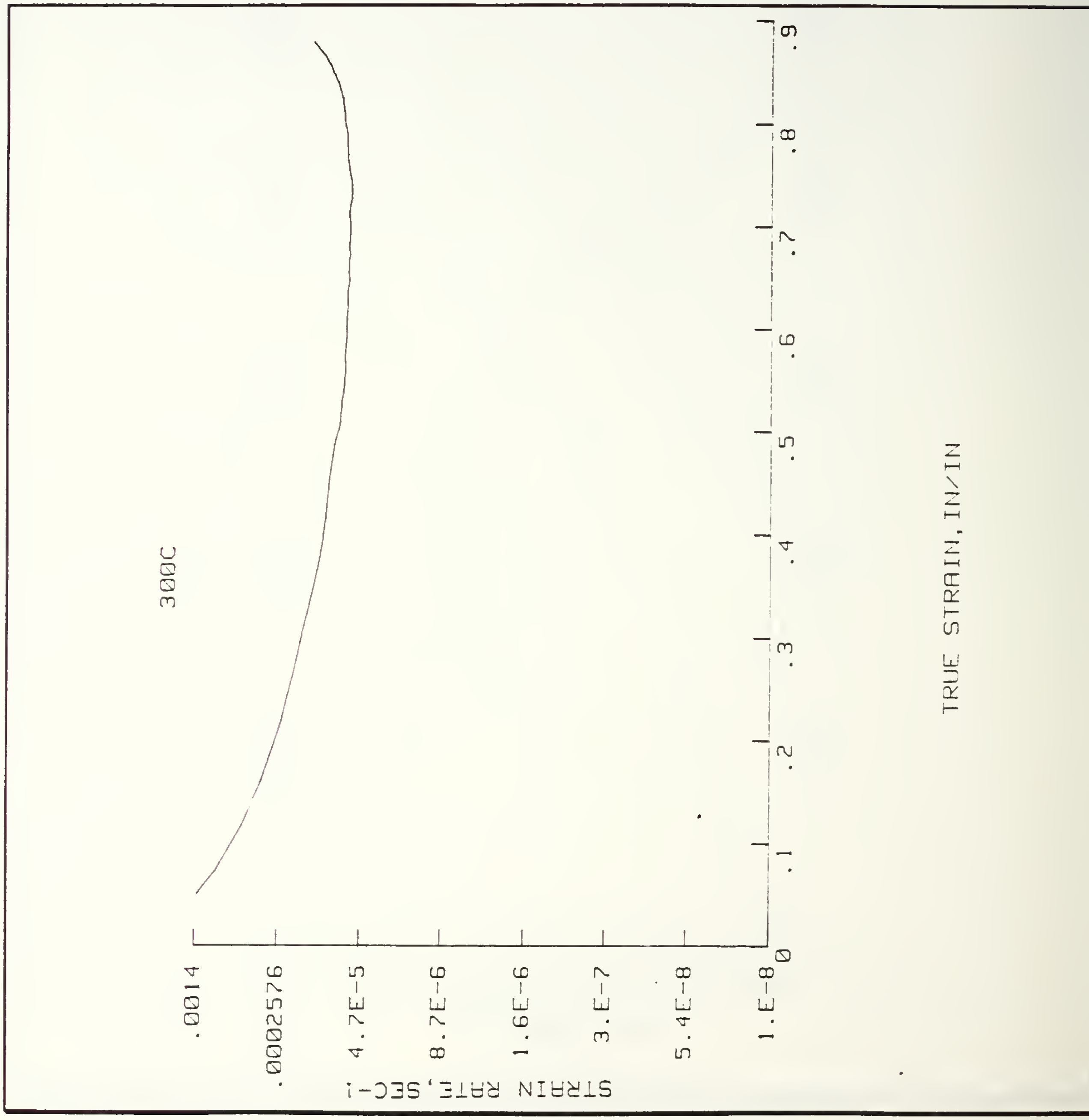

Figure 45. Creep Rate Curve at 300°C for a Stress of 21.2 MPa:

$\dot{\varepsilon}_{min}$ = 6.10 x 10-5 sec-1

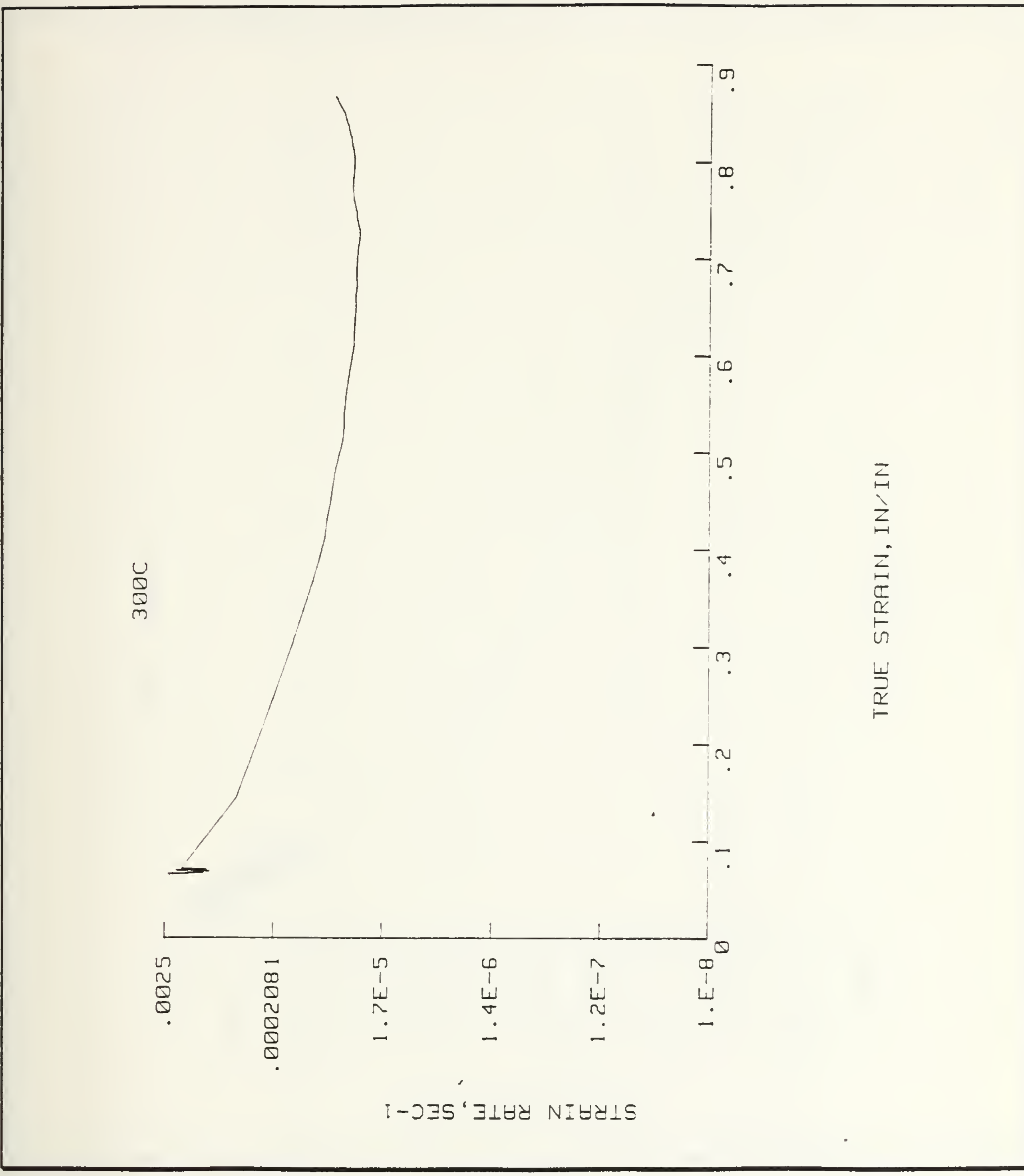

Figure 46. Creep Rate Curve at 300°C for a Stress of 19.0 MPa:

$\dot{\varepsilon}_{min} = 3.32 \times 10^{-5}$ sec^{-1}

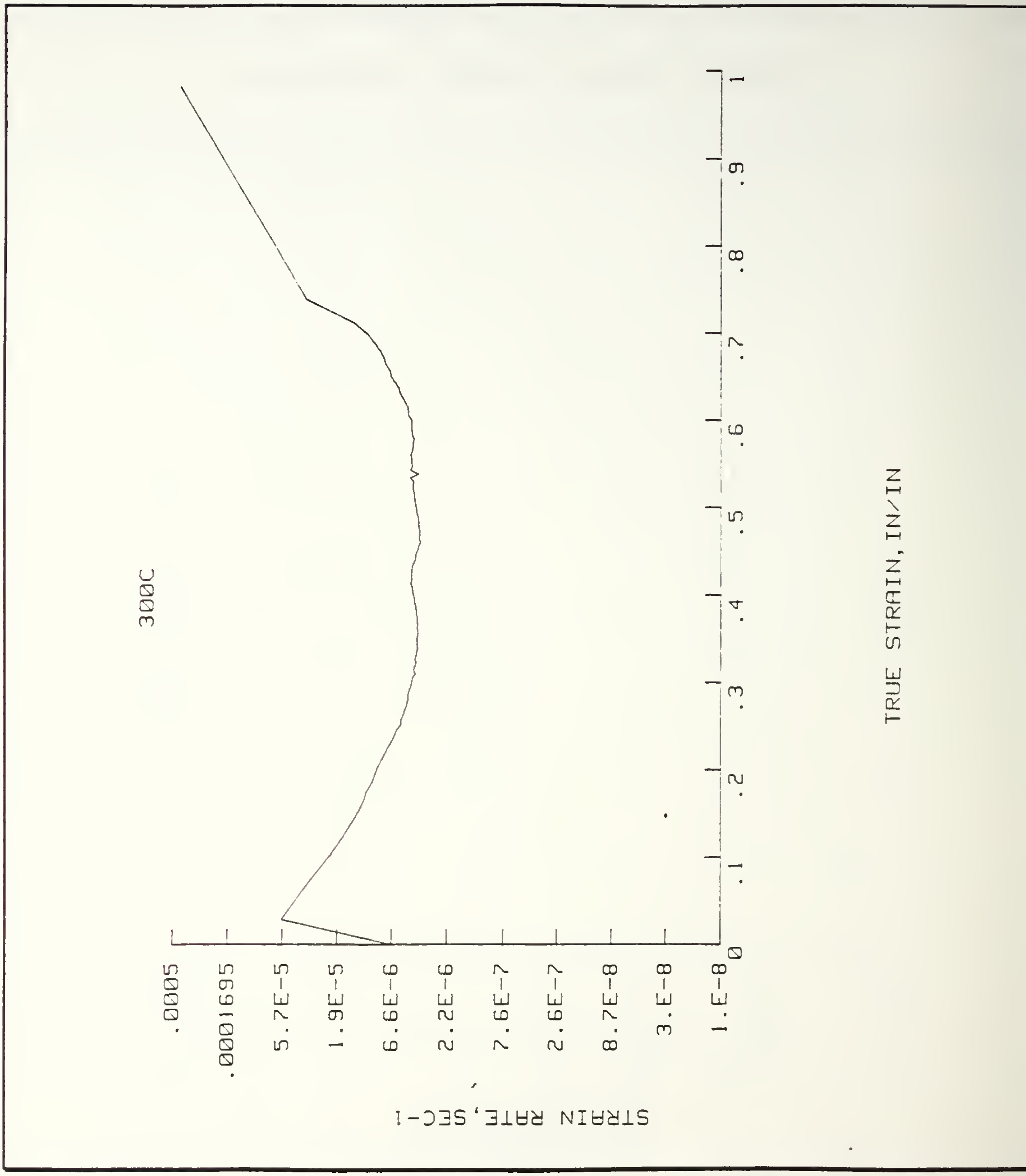

Figure 47. Creep Rate Curve at 300°C for a Stress of 13.0 MPa:

$\dot{\varepsilon}_{min} = 3.76 \times 10^{-6}\ sec^{-1}$

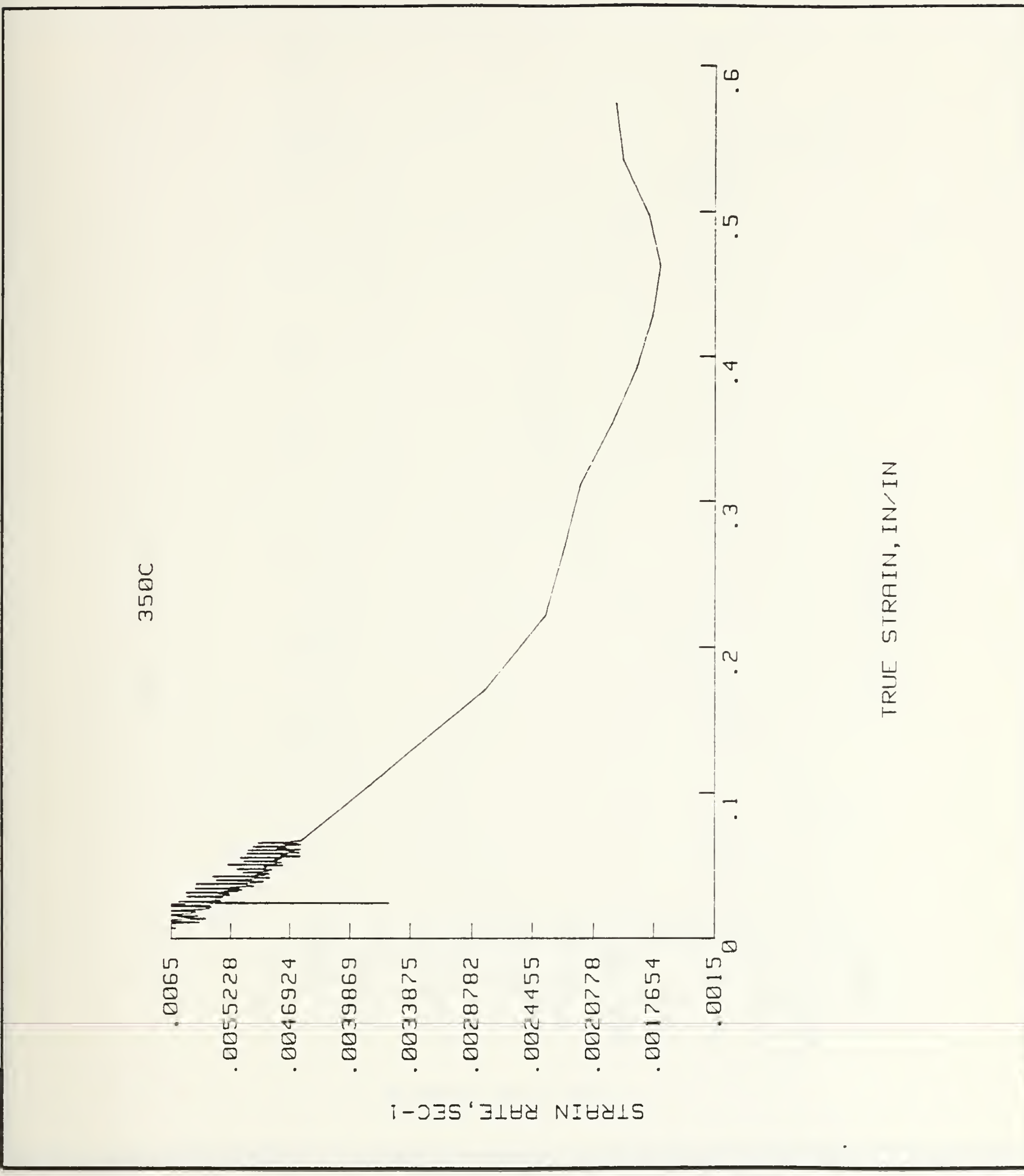

Figure 48. Creep Rate Curve at 350°C for a Stress of 21.2 MPa:

$\dot{\varepsilon}_{min} = 4.96 \times 10^{-3}\ sec^{-1}$

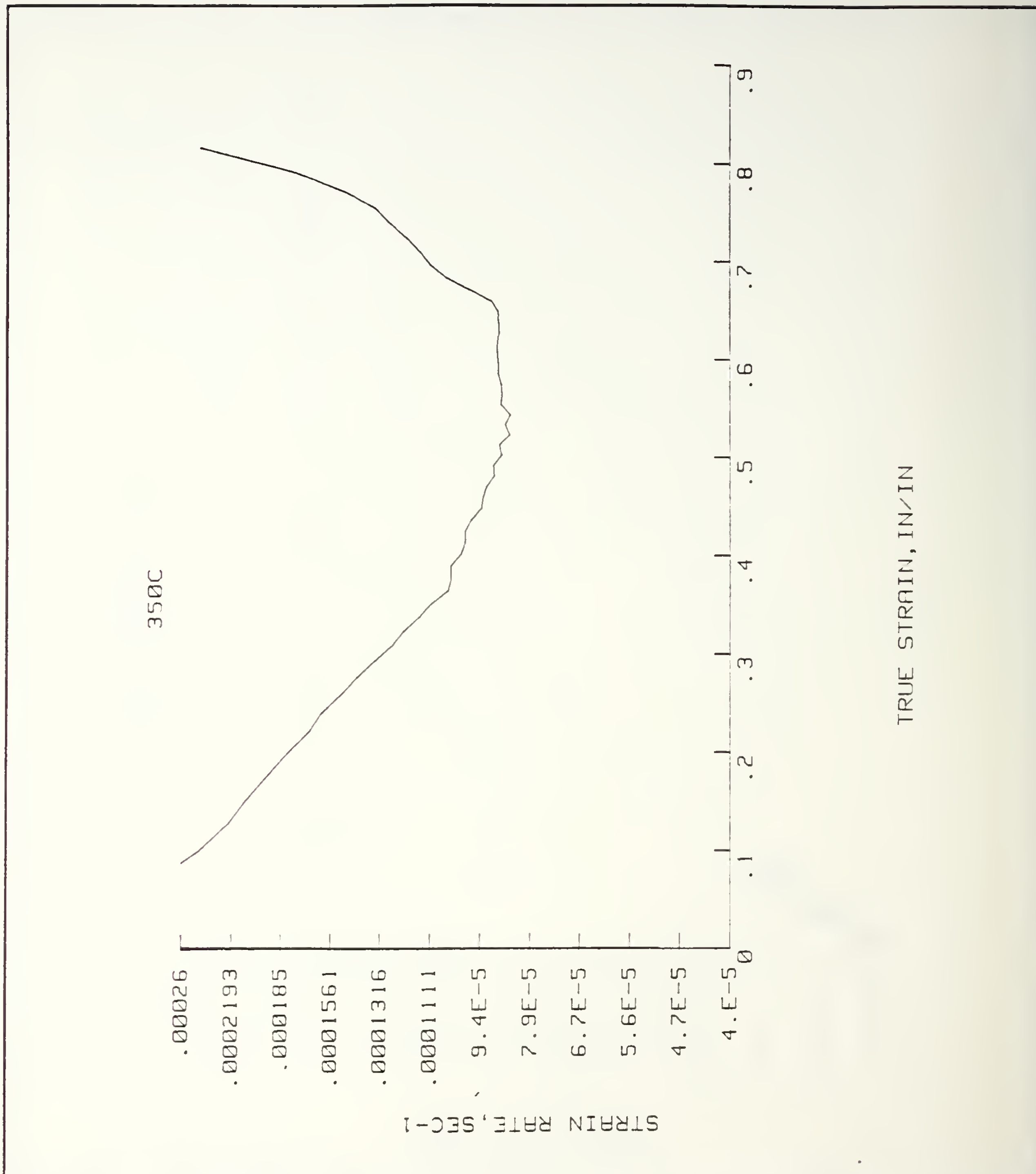

Figure 49. Creep Rate Curve at 350°C for a Stress of 12.9 MPa:

$\dot{\varepsilon}_{min} = 8.57 \times 10^{-5}$ sec^{-1}

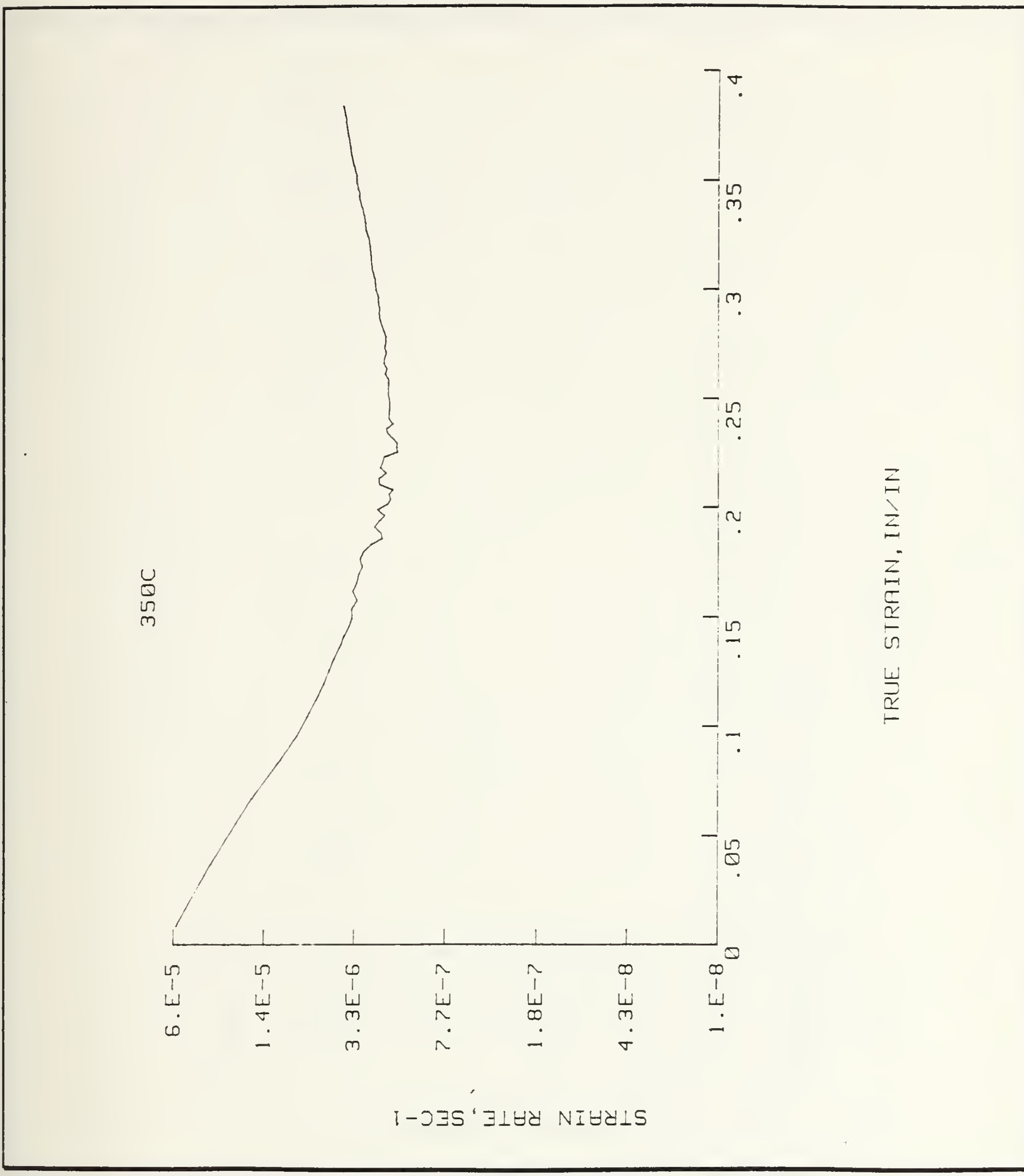

Figure 50. Creep Rate Curve at 350°C for a Stress of 7.00 MPa:

$\dot{\varepsilon}_{min} = 1.94 \times 10^{-6}$ sec^{-1}

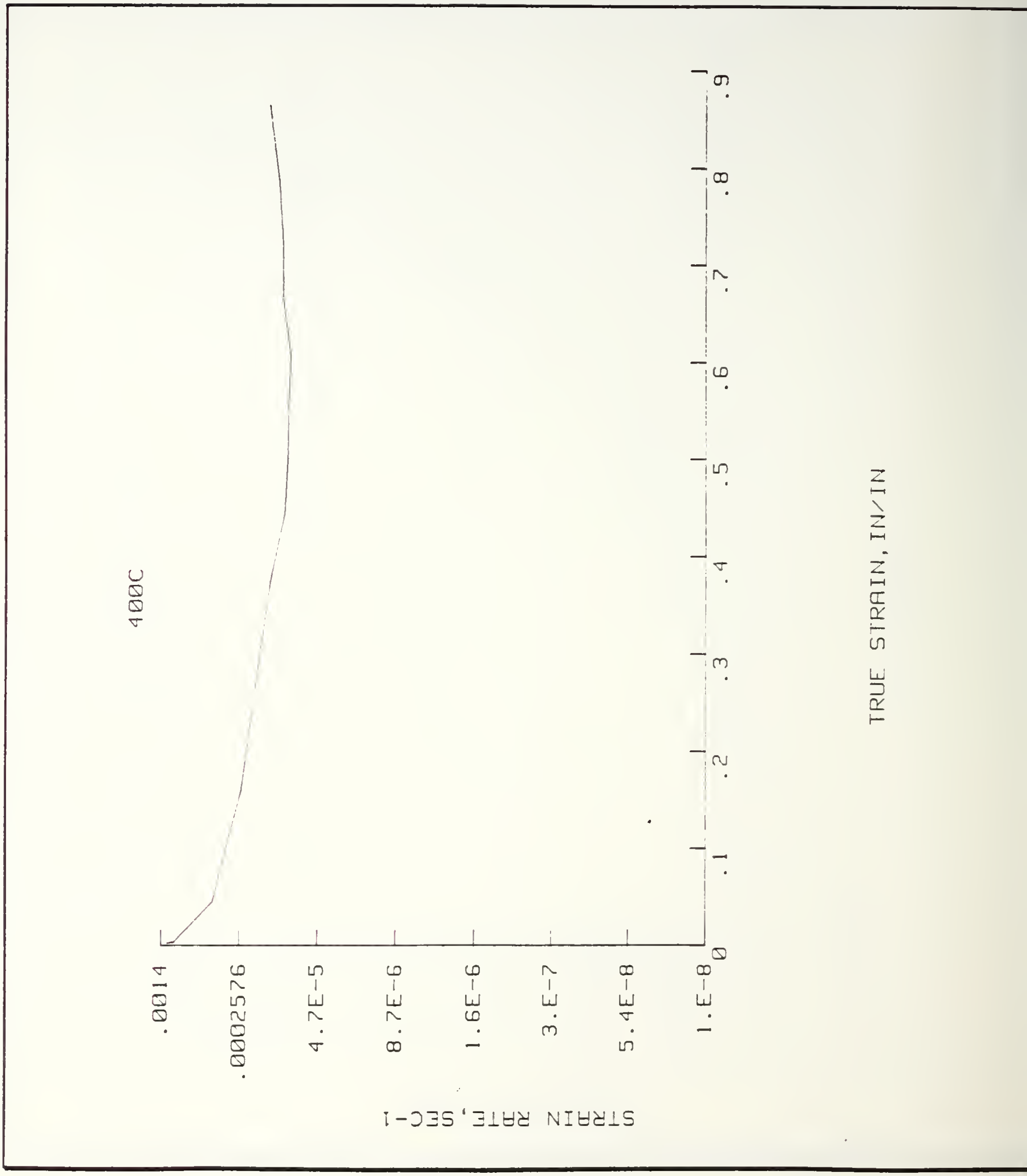

Figure 51. Creep Rate Curve at 400°C for a Stress of 7.10 MPa:

$\dot{\varepsilon}_{min} = 9.66 \times 10^{-5}\ sec^{-1}$

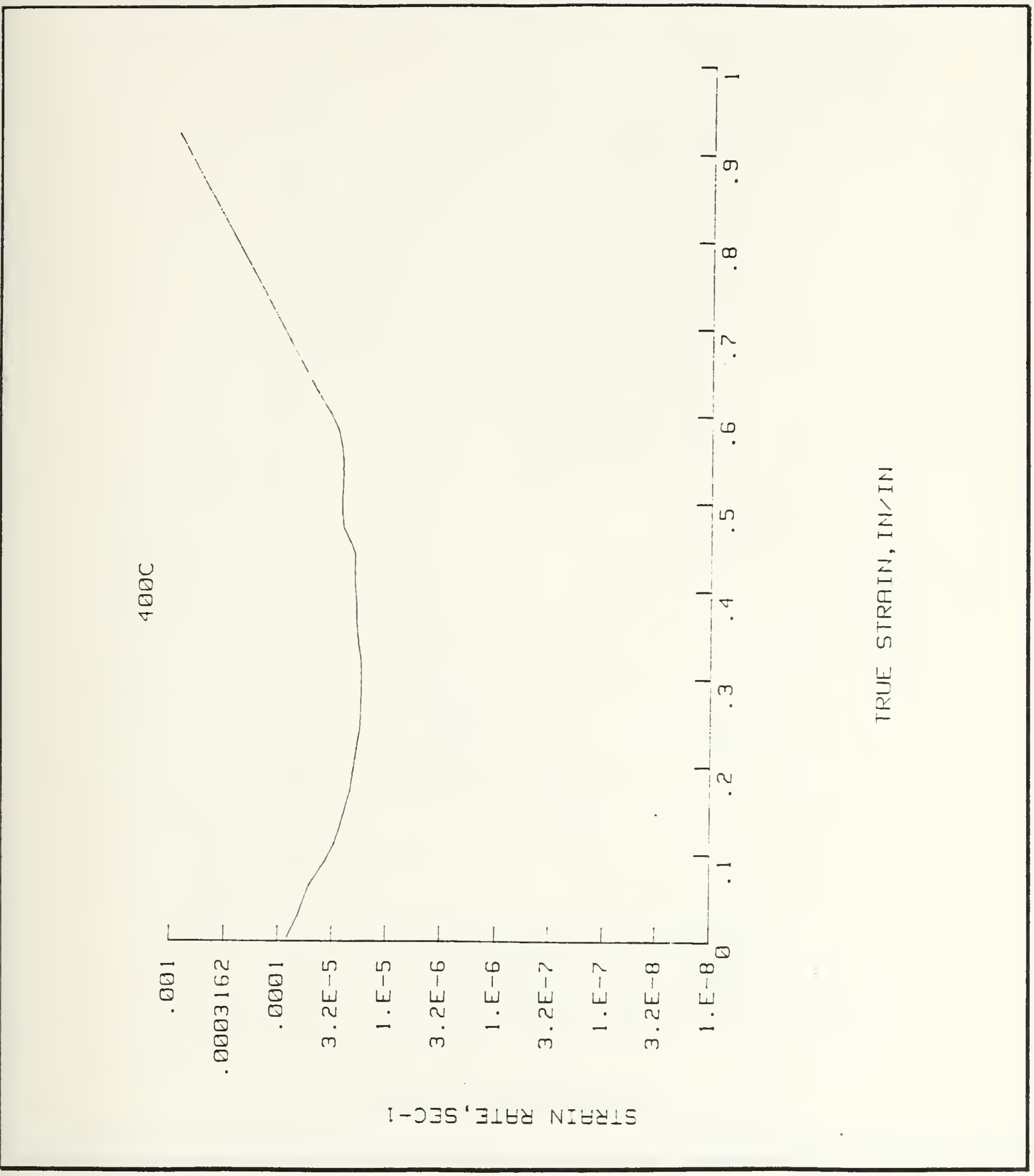

Figure 52. Creep Rate Curve at 400°C for a Stress of 5.27 MPa:

$\dot{\varepsilon}_{min} = 1.73 \times 10^{-5}\ sec^{-1}$

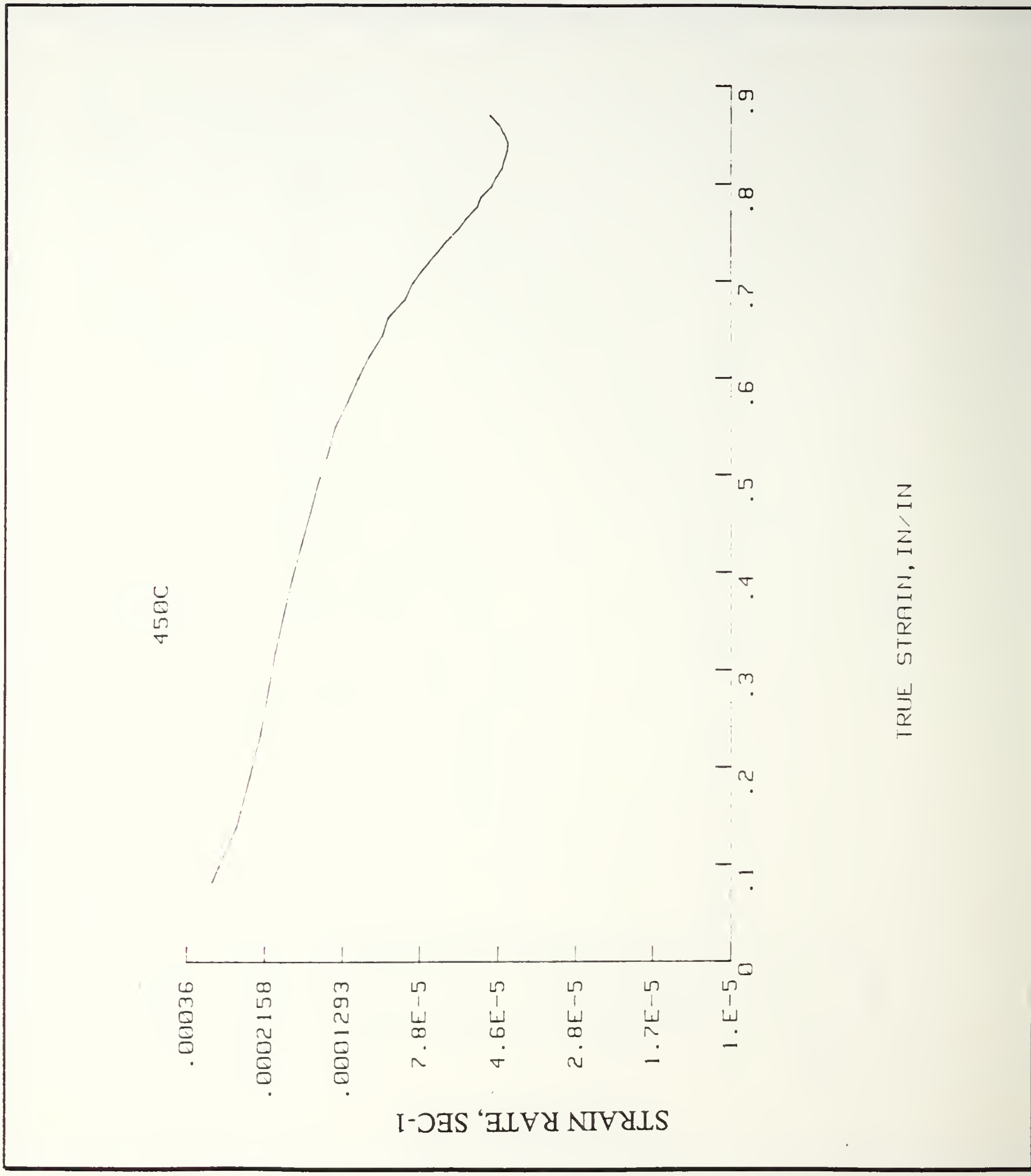

Figure 53. Creep Rate Curve at 450°C for a Stress of 2.35 MPa:

$\dot{\varepsilon}_{min} = 4.37 \times 10^{-5}\ sec^{-1}$

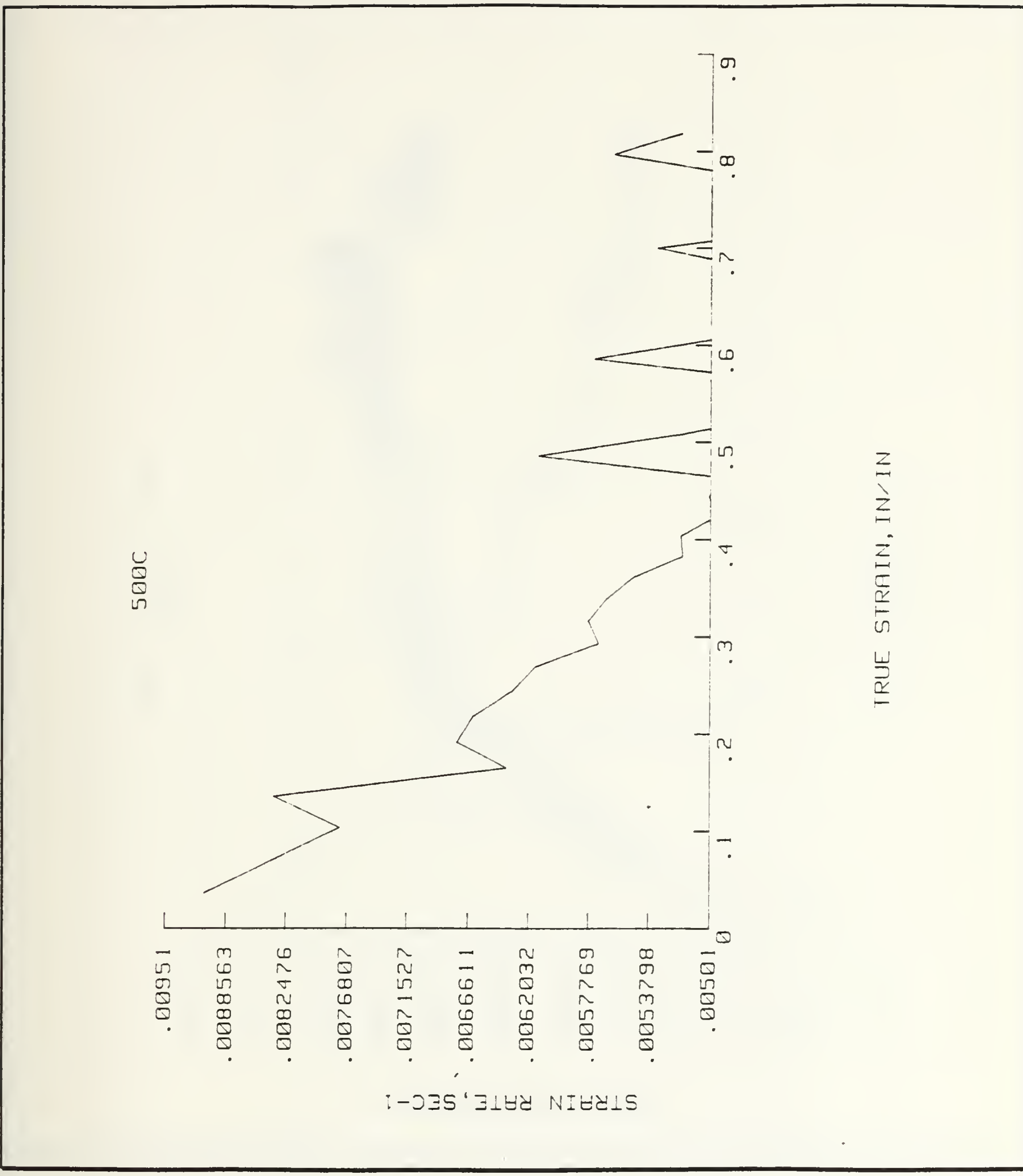

Figure 54. Creep Rate Curve at 500°C for a Stress of 5.48 MPa:

$$\dot{\varepsilon}_{min} = 4.83 \times 10^{-3} \text{ sec}^{-1}$$

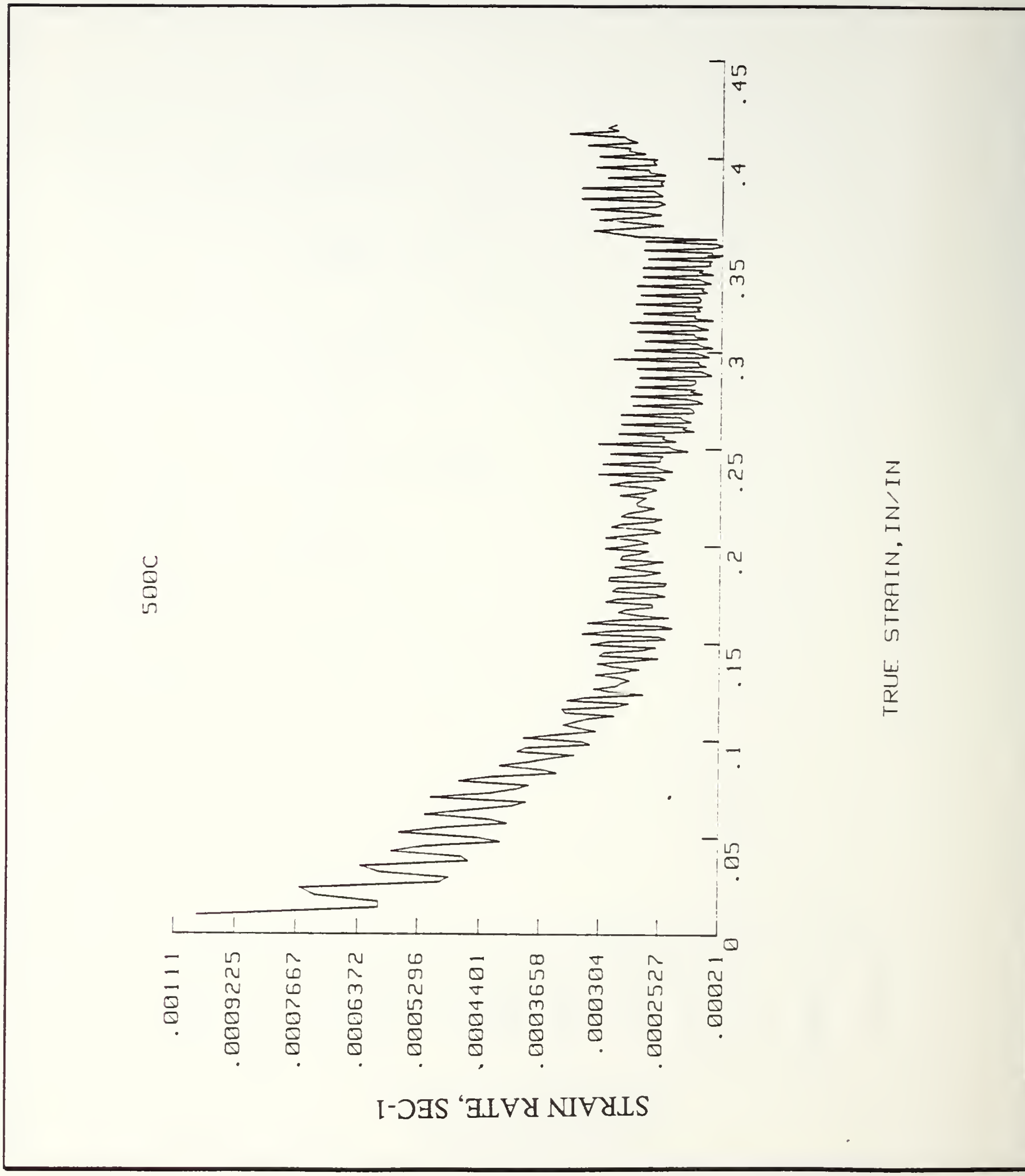

Figure 55. Creep Rate Curve at 500°C for a Stress of 3.02 MPa:

$\dot{\varepsilon}_{min} = 2.43 \times 10^{-4}\ sec^{-1}$

Figure 56. Creep Rate Curve at 500°C for a Stress of 2.25 MPa:

$\dot{\varepsilon}_{min} = 6.36 \times 10^{-5}\ sec^{-1}$

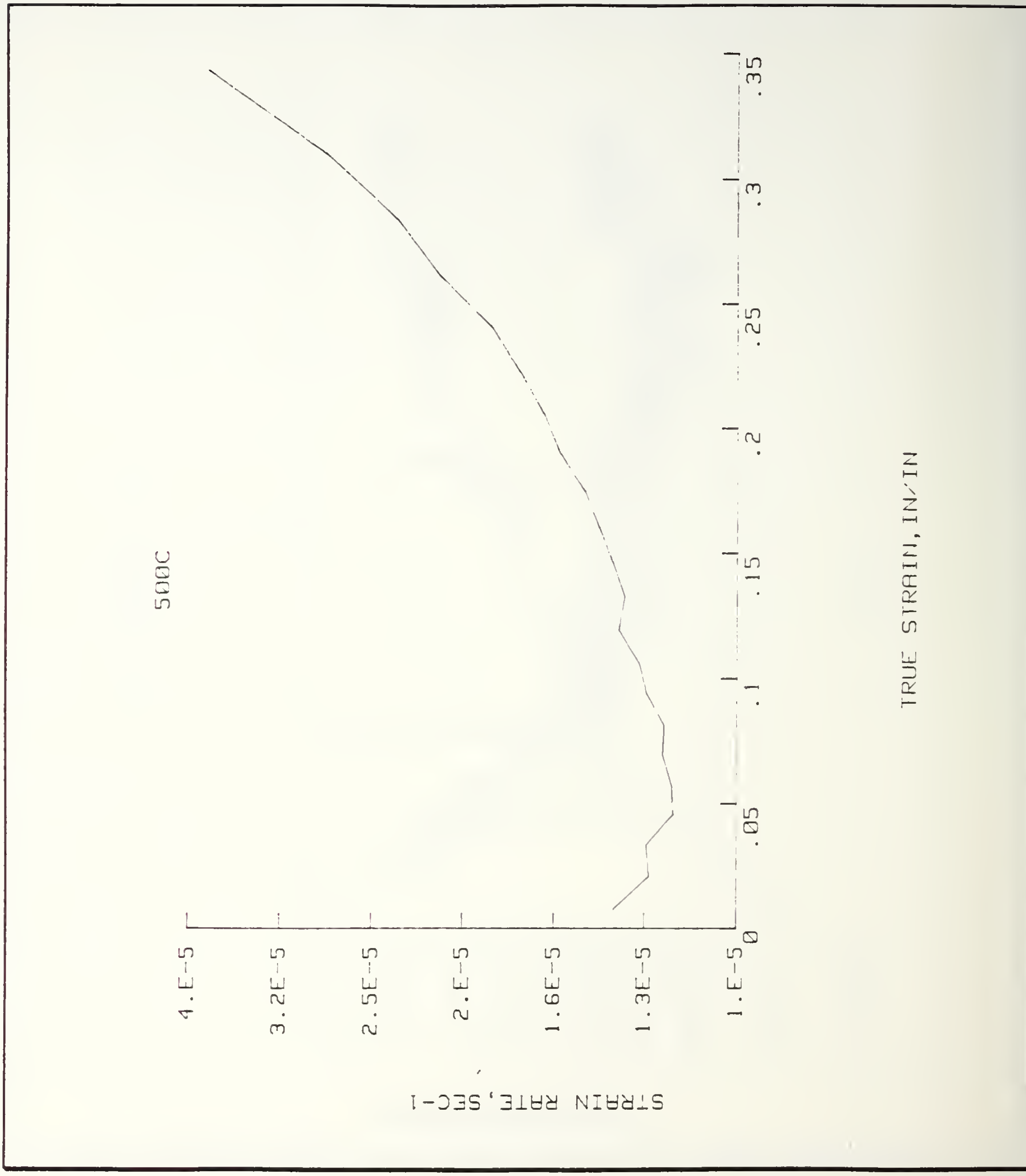

Figure 57. Creep Rate Curve at 500°C for a Stress of 1.84 MPa:

$\dot{\varepsilon}_{min} = 1.17 \times 10^{-5}\ sec^{-1}$

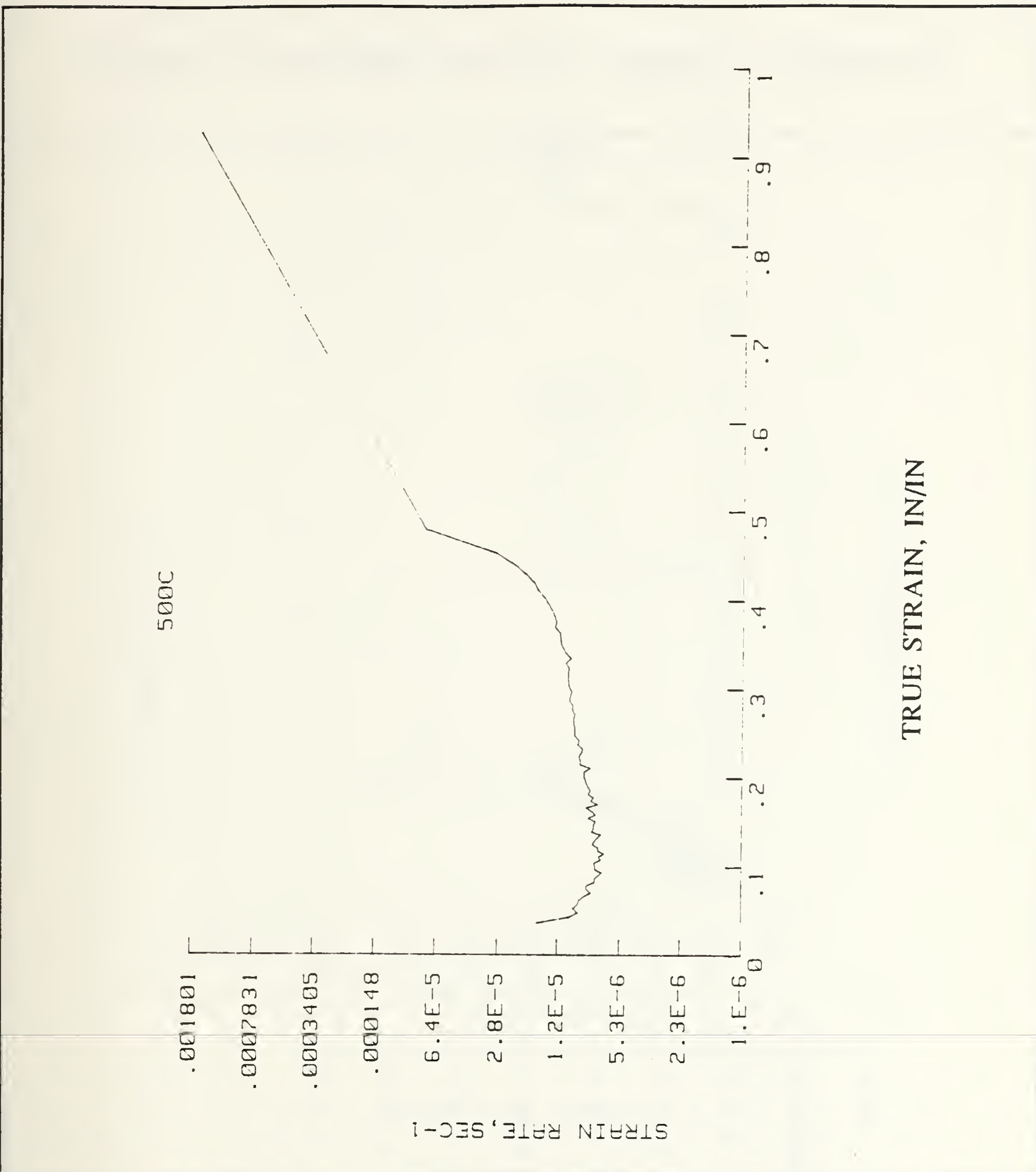

Figure 58. Creep Rate Curve at 500^{o}C for a Stress of 1.63 MPa:

$$\dot{\varepsilon}_{min} = 6.52 \times 10^{-6} \text{ sec}^{-1}$$

APPENDIX E. TEMP. CYCLING CREEP RATE CURVES

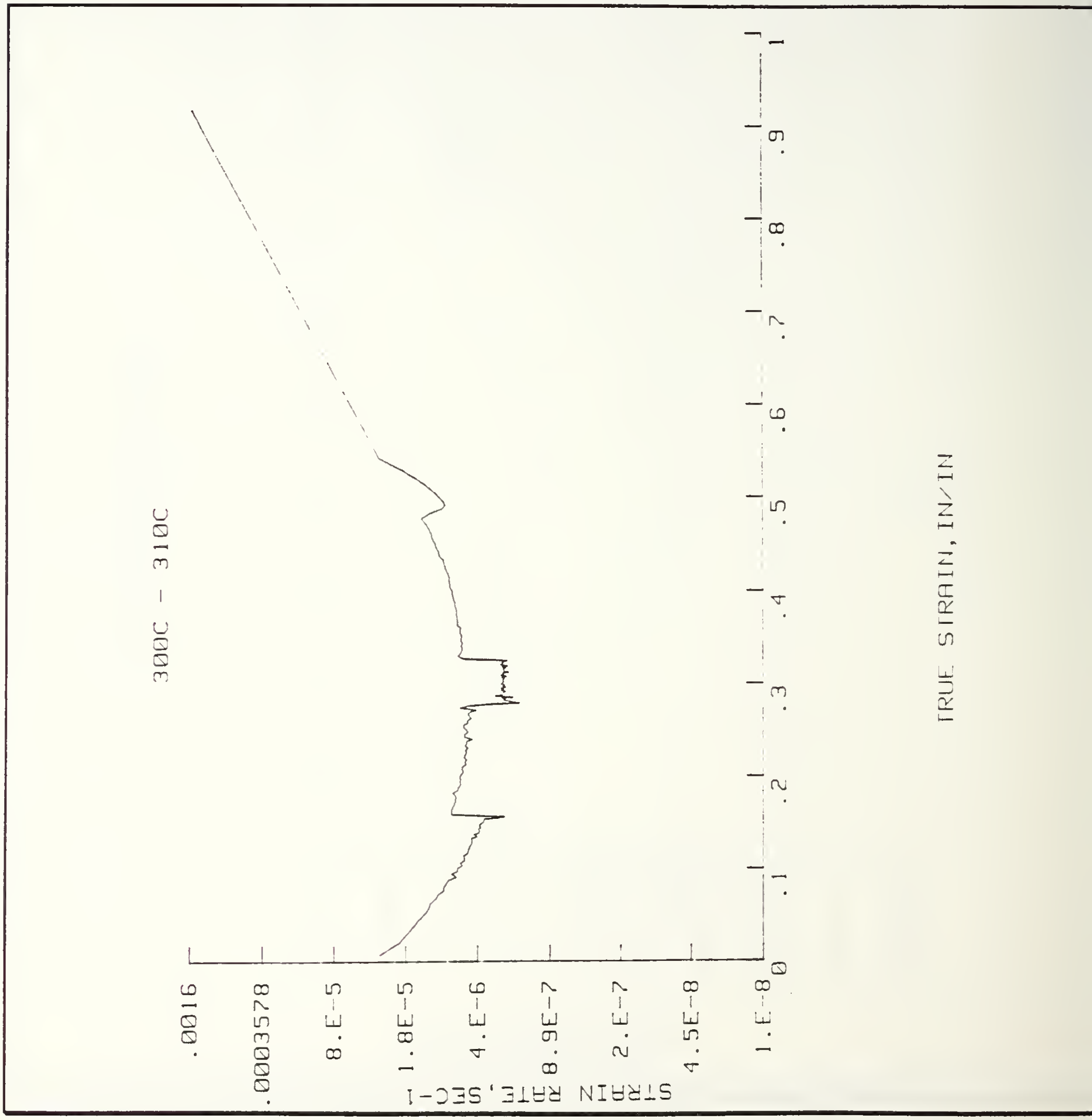

Figure 59. Creep Rate Curve at 300-310^{o}C for a Stress of 11.9 MPa:

$\dot{\varepsilon}_1 = 2.46 \times 10^{-6}$ sec^{-1} & $\dot{\varepsilon}_2 = 4.92 \times 10^{-6}$ sec^{-1}

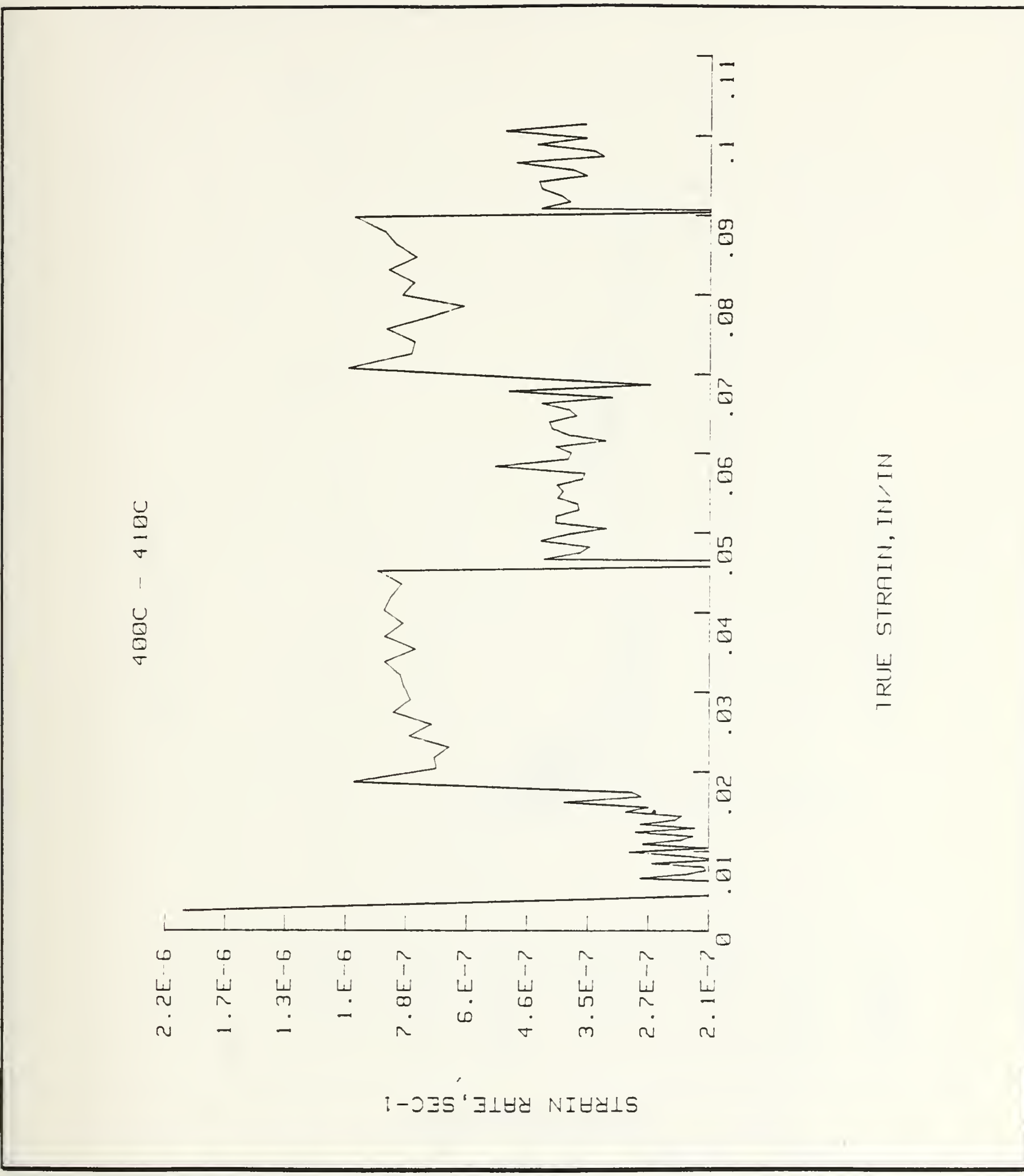

Figure 60. Creep Rate Curve at 400-410°C for a Stress of 3.03 MPa:

$\dot{\varepsilon}_1 = 4.02 \times 10^{-7}$ sec^{-1} & $\dot{\varepsilon}_2 = 7.90 \times 10^{-7}$ sec^{-1}

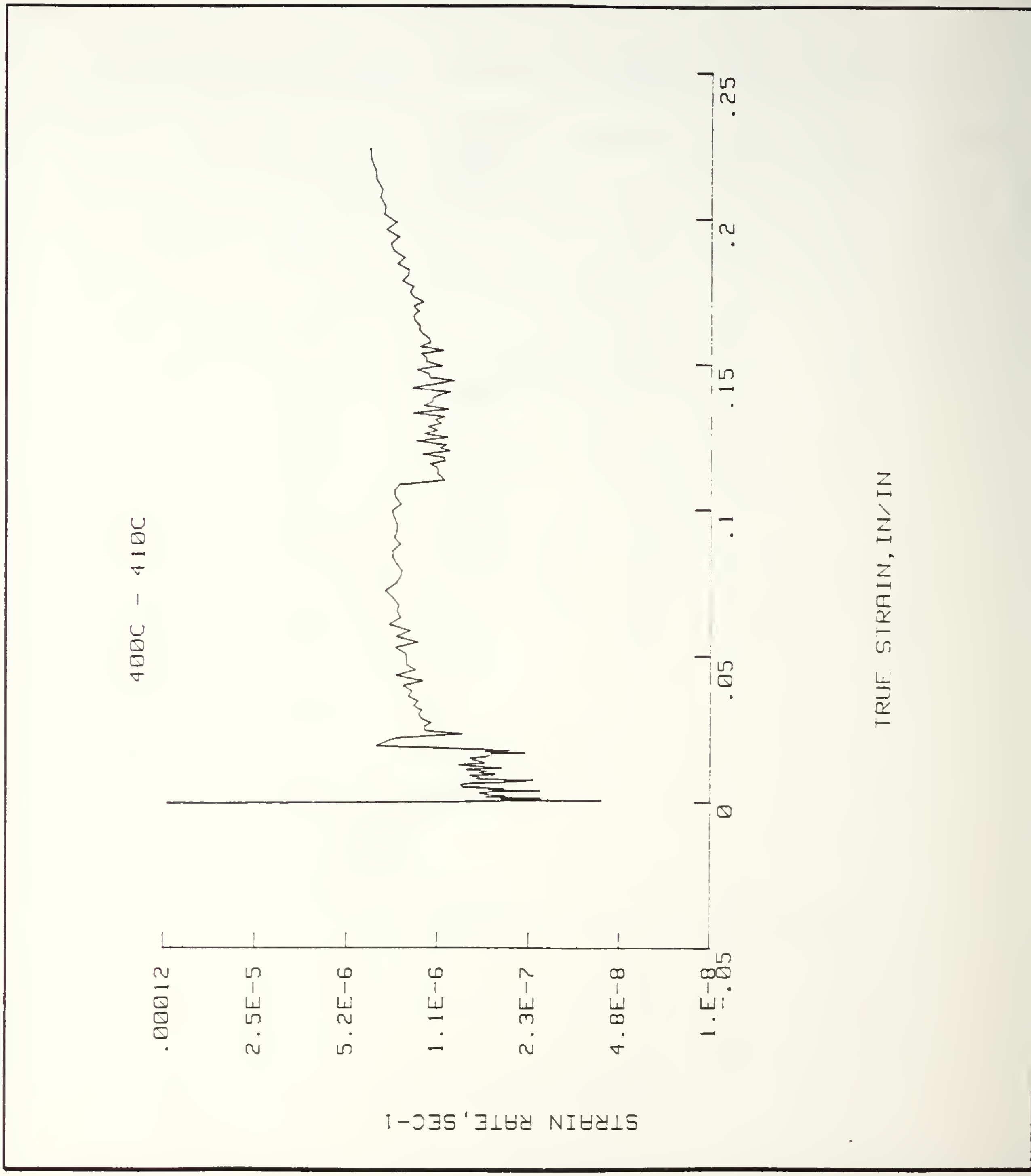

Figure 61. Creep Rate Curve at 400-410°C for a Stress of 3.03 MPa:

$\dot{\varepsilon}_1 = 1.20 \times 10^{-6}\ \mathrm{sec}^{-1}$ & $\dot{\varepsilon}_2 = 2.21 \times 10^{-6}\ \mathrm{sec}^{-1}$

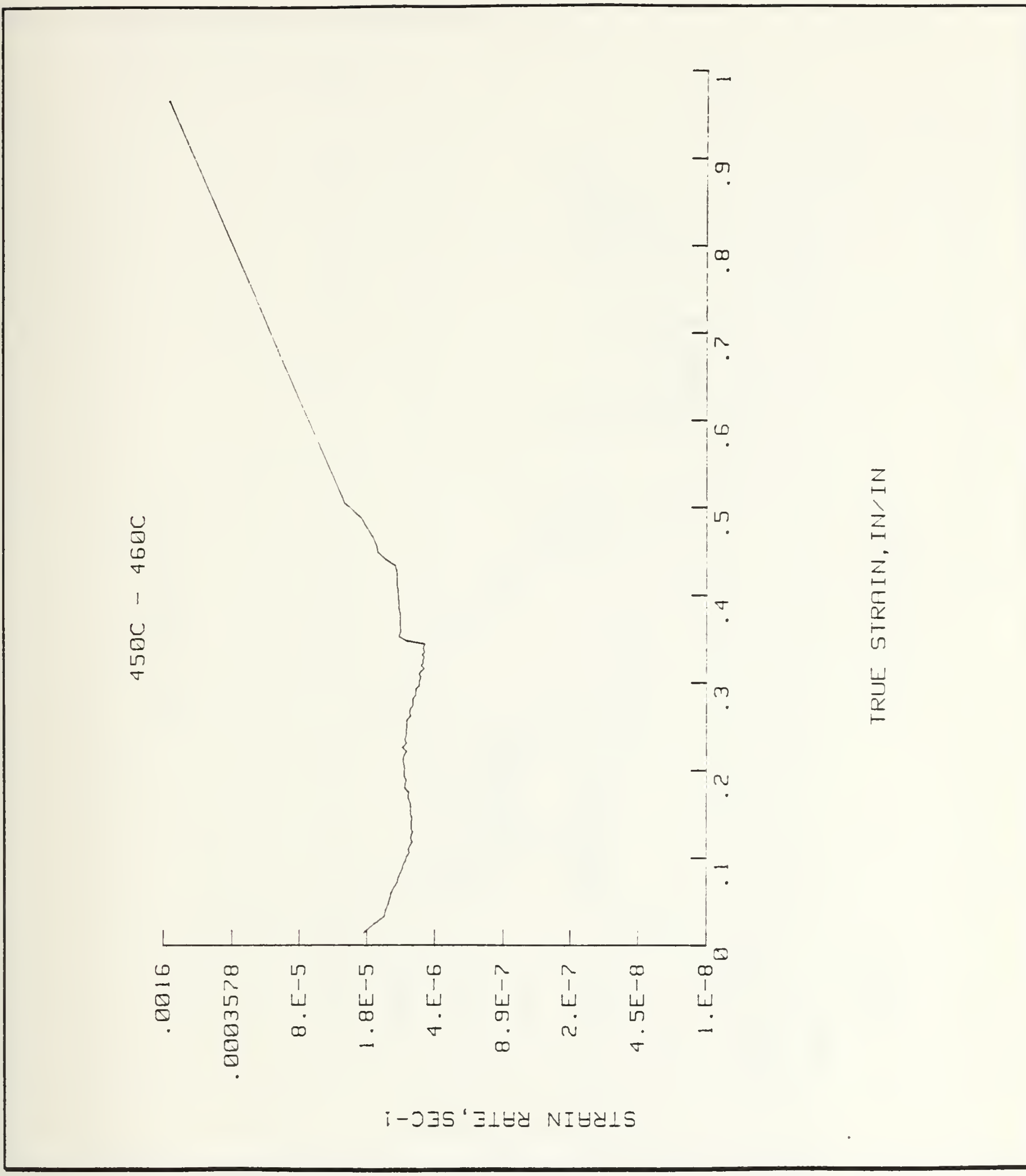

Figure 62. Creep Rate Curve at 450-460°C for a Stress of 2.46 MPa:

$\dot{\varepsilon}_1 = 8.73 \times 10^{-6}\ \text{sec}^{-1}$ & $\dot{\varepsilon}_2 = 5.19 \times 10^{-6}\ \text{sec}^{-1}$

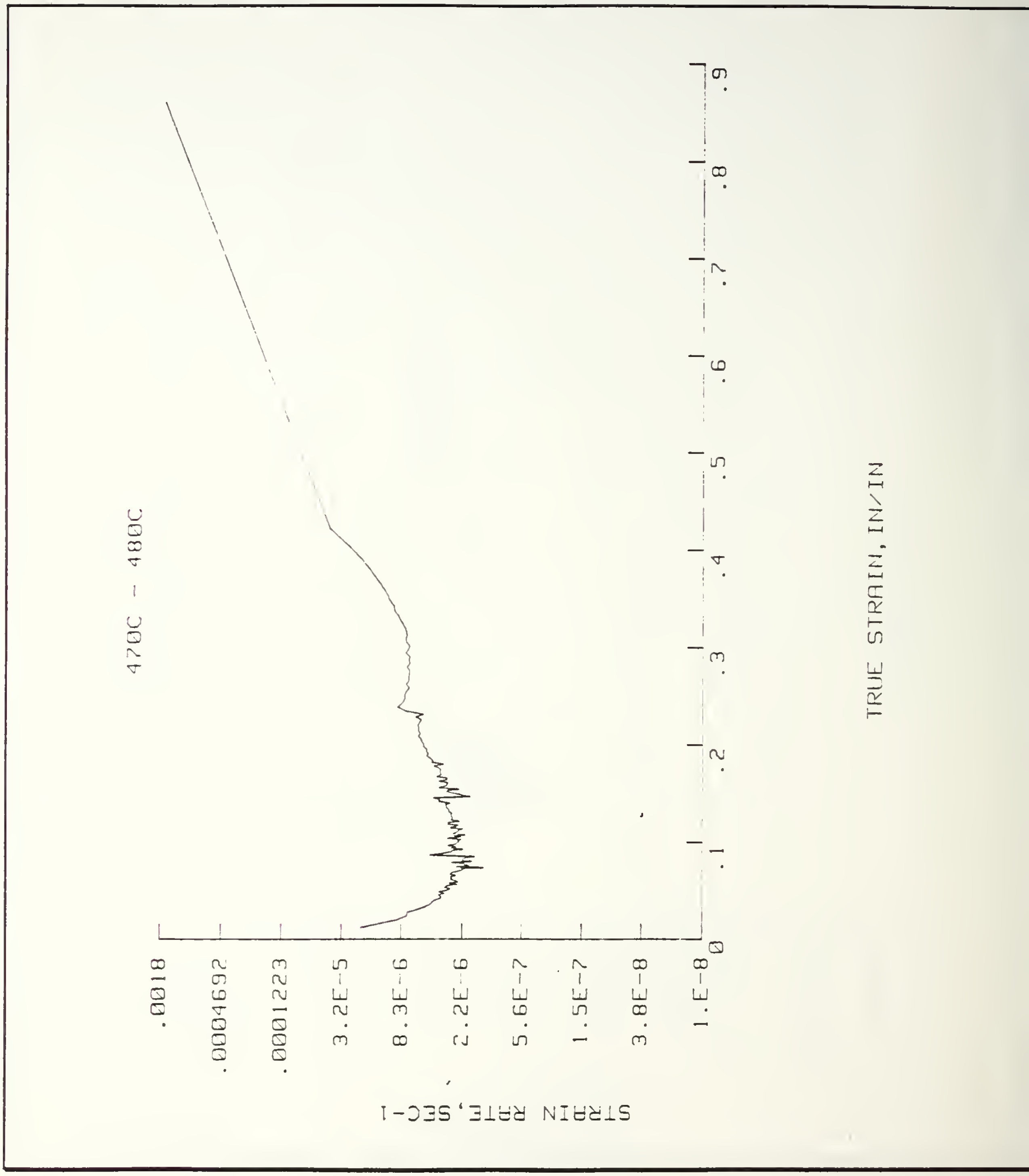

Figure 63. Creep Rate Curve at 470-480^{o}C for a Stress of 2.03 MPa:

$\dot{\varepsilon}_1 = 2.13 \times 10^{-6}\ \mathrm{sec}^{-1}$ & $\dot{\varepsilon}_2 = 2.52 \times 10^{-6}\ \mathrm{sec}^{-1}$

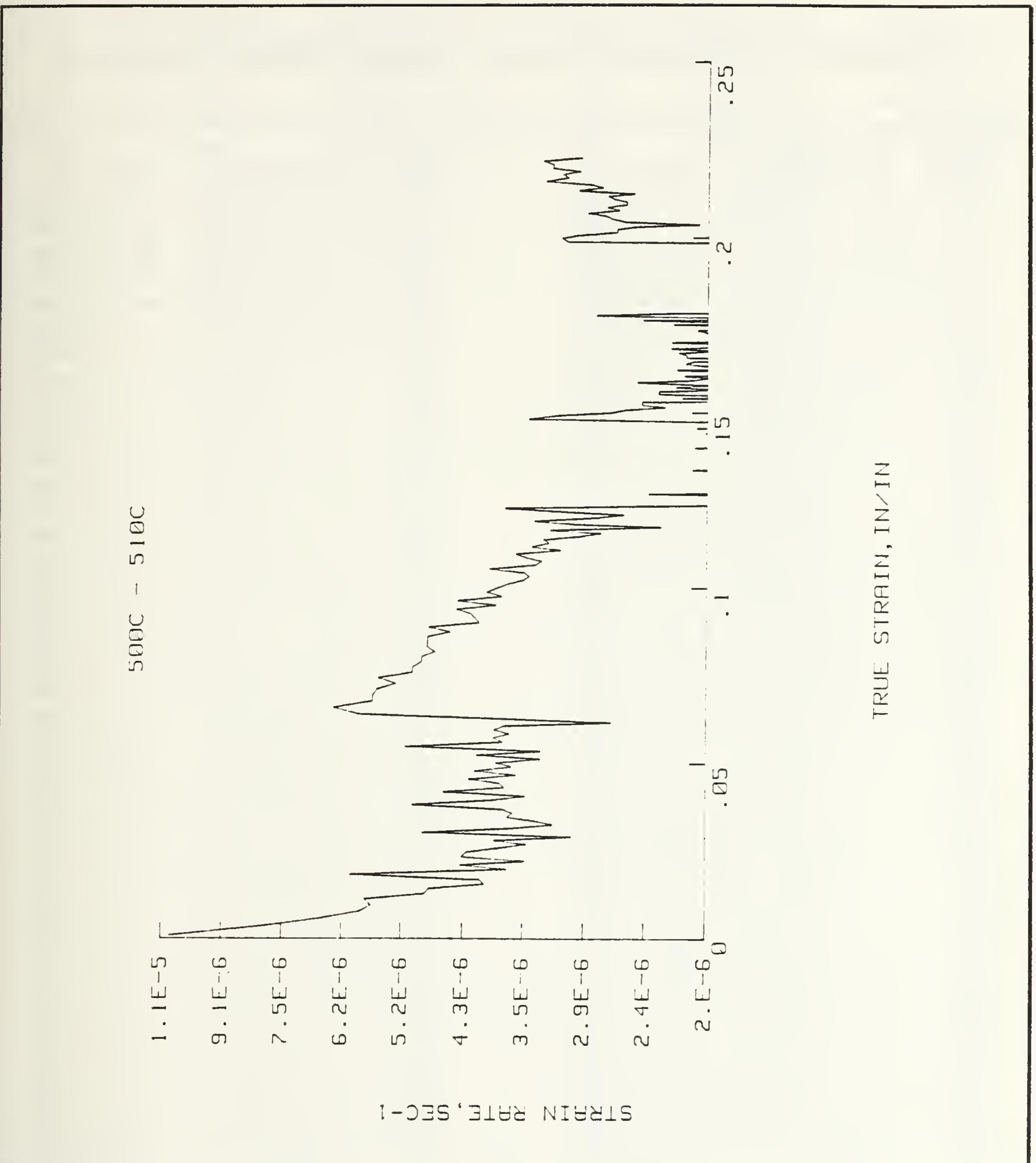

Figure 64. Creep Rate Curve at 500-510^{o}C for a Stress of 1.64 MPa:

$\dot{\varepsilon}_1 = 1.99 \times 10^{-6}$ sec^{-1} & $\dot{\varepsilon}_2 = 2.77 \times 10^{-6}$ sec^{-1}

APPENDIX F. EXAMPLE DATA TABLES FROM PROGRAM

FILENAME IS TEST240

RDG #	TRUESTRAIN	TIME,SEC	RDG #	TRUESTRAIN	TIME,SEC
2	+7.353E-03	+5.010E+00	4	+1.550E-02	+1.501E+01
6	+2.211E-02	+2.501E+01	8	+2.837E-02	+3.501E+01
10	+3.376E-02	+4.501E+01	12	+3.920E-02	+5.502E+01
14	+4.440E-02	+6.502E+01	16	+4.904E-02	+7.502E+01
18	+5.407E-02	+8.502E+01	20	+5.853E-02	+9.502E+01
22	+6.328E-02	+1.050E+02	24	+6.753E-02	+1.150E+02
26	+7.199E-02	+1.250E+02	28	+7.607E-02	+1.350E+02
30	+8.031E-02	+1.450E+02	32	+8.416E-02	+1.550E+02
34	+8.805E-02	+1.651E+02	36	+9.170E-02	+1.750E+02
38	+9.531E-02	+1.850E+02	40	+9.878E-02	+1.950E+02
42	+1.023E-01	+2.051E+02	44	+1.056E-01	+2.151E+02
46	+1.089E-01	+2.251E+02	48	+1.121E-01	+2.351E+02
50	+1.153E-01	+2.451E+02	52	+1.184E-01	+2.551E+02
54	+1.215E-01	+2.651E+02	56	+1.244E-01	+2.751E+02
58	+1.274E-01	+2.851E+02	60	+1.303E-01	+2.951E+02
62	+1.331E-01	+3.051E+02	64	+1.360E-01	+3.151E+02
66	+1.388E-01	+3.251E+02	68	+1.417E-01	+3.351E+02
70	+1.445E-01	+3.451E+02	72	+1.474E-01	+3.551E+02
74	+1.502E-01	+3.651E+02	76	+1.529E-01	+3.751E+02
78	+1.558E-01	+3.851E+02	80	+1.585E-01	+3.951E+02
82	+1.613E-01	+4.051E+02	84	+1.640E-01	+4.151E+02
86	+1.668E-01	+4.251E+02	88	+1.695E-01	+4.351E+02
90	+1.723E-01	+4.451E+02	92	+1.750E-01	+4.551E+02
94	+1.777E-01	+4.651E+02	96	+1.804E-01	+4.751E+02
98	+1.831E-01	+4.851E+02	100	+1.859E-01	+4.951E+02
102	+1.886E-01	+5.051E+02	104	+1.913E-01	+5.151E+02
106	+1.940E-01	+5.251E+02	108	+1.968E-01	+5.351E+02
110	+1.996E-01	+5.451E+02	112	+2.023E-01	+5.551E+02
114	+2.051E-01	+5.651E+02	116	+2.078E-01	+5.751E+02
118	+2.105E-01	+5.851E+02	120	+2.133E-01	+5.951E+02
122	+2.159E-01	+6.051E+02	124	+2.187E-01	+6.151E+02
126	+2.213E-01	+6.251E+02	128	+2.240E-01	+6.351E+02
130	+2.268E-01	+6.451E+02	132	+2.294E-01	+6.551E+02
134	+2.322E-01	+6.651E+02	136	+2.348E-01	+6.751E+02
138	+2.376E-01	+6.851E+02	140	+2.401E-01	+6.951E+02
142	+2.429E-01	+7.052E+02	144	+2.454E-01	+7.151E+02
146	+2.482E-01	+7.251E+02	148	+2.506E-01	+7.352E+02
150	+2.533E-01	+7.451E+02	152	+2.558E-01	+7.552E+02
154	+2.585E-01	+7.652E+02	156	+2.608E-01	+7.752E+02
158	+2.634E-01	+7.852E+02	160	+2.657E-01	+7.952E+02
162	+2.684E-01	+8.052E+02	164	+2.706E-01	+8.152E+02

Figure 65. Creep Data Table

166	+2.732E-01	+8.252E+02	168	+2.754E-01	+8.352E+02
170	+2.780E-01	+8.452E+02	172	+2.803E-01	+8.552E+02
174	+2.828E-01	+8.652E+02	176	+2.850E-01	+8.752E+02
178	+2.875E-01	+8.852E+02	180	+2.897E-01	+8.952E+02
182	+2.922E-01	+9.052E+02	184	+2.944E-01	+9.152E+02
186	+2.970E-01	+9.252E+02	188	+2.992E-01	+9.352E+02
190	+3.018E-01	+9.452E+02	192	+3.040E-01	+9.552E+02
194	+3.064E-01	+9.652E+02	196	+3.087E-01	+9.752E+02
198	+3.112E-01	+9.852E+02	200	+3.134E-01	+9.952E+02
202	+3.159E-01	+1.005E+03	204	+3.181E-01	+1.015E+03
206	+3.206E-01	+1.025E+03	208	+3.229E-01	+1.035E+03
210	+3.254E-01	+1.045E+03	212	+3.276E-01	+1.055E+03
214	+3.301E-01	+1.065E+03	216	+3.323E-01	+1.075E+03
218	+3.348E-01	+1.085E+03	220	+3.370E-01	+1.095E+03
222	+3.395E-01	+1.105E+03	224	+3.417E-01	+1.115E+03
226	+3.441E-01	+1.125E+03	228	+3.463E-01	+1.135E+03
230	+3.487E-01	+1.145E+03	232	+3.508E-01	+1.155E+03
234	+3.533E-01	+1.165E+03	236	+3.554E-01	+1.175E+03
238	+3.578E-01	+1.185E+03	240	+3.602E-01	+1.195E+03
242	+3.633E-01	+1.205E+03	244	+3.659E-01	+1.215E+03
246	+3.688E-01	+1.225E+03	248	+3.714E-01	+1.235E+03
250	+3.744E-01	+1.245E+03	252	+3.769E-01	+1.255E+03
254	+3.798E-01	+1.265E+03	256	+3.824E-01	+1.275E+03
258	+3.853E-01	+1.285E+03	260	+3.878E-01	+1.295E+03
262	+3.906E-01	+1.305E+03	264	+3.932E-01	+1.315E+03
266	+3.960E-01	+1.325E+03	268	+3.986E-01	+1.335E+03
270	+4.015E-01	+1.345E+03	272	+4.042E-01	+1.355E+03
274	+4.072E-01	+1.365E+03	276	+4.100E-01	+1.375E+03
278	+4.131E-01	+1.385E+03	280	+4.161E-01	+1.395E+03
282	+4.192E-01	+1.405E+03	284	+4.223E-01	+1.415E+03
286	+4.256E-01	+1.425E+03	288	+4.287E-01	+1.435E+03
290	+4.321E-01	+1.445E+03	292	+4.353E-01	+1.455E+03
294	+4.387E-01	+1.465E+03	296	+4.420E-01	+1.475E+03
298	+4.455E-01	+1.485E+03	300	+4.487E-01	+1.495E+03
302	+4.523E-01	+1.505E+03	304	+4.555E-01	+1.515E+03
306	+4.589E-01	+1.525E+03	308	+4.621E-01	+1.535E+03
310	+4.655E-01	+1.545E+03	312	+4.686E-01	+1.555E+03
314	+4.720E-01	+1.565E+03	316	+4.751E-01	+1.575E+03
318	+4.786E-01	+1.585E+03	320	+4.816E-01	+1.595E+03
322	+4.850E-01	+1.605E+03	324	+4.880E-01	+1.615E+03
326	+4.913E-01	+1.625E+03	328	+4.944E-01	+1.635E+03
330	+4.977E-01	+1.645E+03	332	+5.009E-01	+1.655E+03
334	+5.043E-01	+1.665E+03	336	+5.075E-01	+1.675E+03
338	+5.111E-01	+1.685E+03	340	+5.145E-01	+1.695E+03

Figure 65. Creep Data Table (Continued)

FILENAME IS TEST240

INTERVAL	AVG STRAIN	STRAIN RATE
2- 12	+2.328E-02	+6.368E-04
12- 22	+5.124E-02	+4.814E-04
22- 32	+7.372E-02	+4.176E-04
32- 42	+9.324E-02	+3.631E-04
42- 52	+1.104E-01	+3.216E-04
52- 62	+1.257E-01	+2.935E-04
62- 72	+1.402E-01	+2.857E-04
72- 82	+1.544E-01	+2.793E-04
82- 92	+1.682E-01	+2.728E-04
92- 102	+1.818E-01	+2.716E-04
102- 112	+1.954E-01	+2.745E-04
112- 122	+2.091E-01	+2.730E-04
122- 132	+2.227E-01	+2.686E-04
132- 142	+2.361E-01	+2.706E-04
142- 152	+2.494E-01	+2.575E-04
152- 162	+2.621E-01	+2.514E-04
162- 172	+2.743E-01	+2.379E-04
172- 182	+2.862E-01	+2.390E-04
182- 192	+2.981E-01	+2.349E-04
192- 202	+3.099E-01	+2.394E-04
202- 212	+3.218E-01	+2.336E-04
212- 222	+3.335E-01	+2.368E-04
222- 232	+3.452E-01	+2.277E-04
232- 242	+3.571E-01	+2.483E-04
242- 252	+3.701E-01	+2.731E-04
252- 262	+3.838E-01	+2.735E-04
262- 272	+3.974E-01	+2.722E-04
272- 282	+4.117E-01	+3.004E-04
282- 292	+4.273E-01	+3.213E-04
292- 302	+4.438E-01	+3.399E-04
302- 312	+4.605E-01	+3.260E-04
312- 322	+4.768E-01	+3.278E-04
322- 332	+4.929E-01	+3.176E-04
332- 342	+5.095E-01	+3.460E-04
342- 352	+5.278E-01	+3.857E-04
352- 362	+5.480E-01	+4.196E-04
362- 372	+5.695E-01	+4.424E-04
372- 382	+5.928E-01	+4.877E-04
382- 392	+6.178E-01	+5.140E-04
392- 402	+6.465E-01	+6.323E-04
402- 412	+6.832E-01	+8.361E-04
412- 422	+9.756E-01	+1.086E-02
422- 432	+1.247E+00	+1.149E-06

Figure 66. Creep Rate Data Table

APPENDIX G. COMPUTER PROGRAMS FOR CREEP DATA

```
100 READ A,   N,   X1,  L1
110 FOR I= 1 TO N
120 READ X,  Y
130 S = Y/A
140 C = (10*L1)/(X1)
150 E = (X*C)/5
160 S1 = S*(1+E)
170 E1 = LOG(1+E)
180 PRINT TAB(0);X ;TAB(08);Y ;TAB(16);S ;TAB(32);E ;TAB(43);S1;TAB(57);E1
190 NEXT I
200 DATA  .01642    ,  17  ,  314.68    , .721
210 DATA    0       ,   7
220 DATA    5       ,   7.4
230 DATA   10       ,   7.35
240 DATA   15       ,   7.25
250 DATA   20       ,   7.2
255 DATA   44       ,   6.5
260 DATA   68       ,   5.9
270 DATA   92       ,   5.3
280 DATA  116       ,   4.8
290 DATA  140       ,   4.3
300 DATA  164       ,   3.9
310 DATA  188       ,   3.55
320 DATA  212       ,   3.3
330 DATA  236       ,   2.9
340 DATA  260       ,   2.425
350 DATA  284       ,   1.6
360 DATA  308       ,   0
```

Figure 67. Computer Program to Reduce Stress-Strain Data From Load-Time Data

```
10    ! Program for running two creep machines
15    ! Written 10-06-88 Tom Kellogg
20    ! Revised 10-06-89 LT EARL F. GOODSON, SR.
25    ! Stored as DT_CREPT
30    OUTPUT 709;"SI"
35    DIM On_off(2),Unit$(2)[10]
40    DIM Strain_1(5000),Strain_2(5000),Tyme_1(5000),Tyme_2(5000)
45    DIM T_0(2),T_e(2),T_i(2),Rdg(2)
50    Nr_pts=5000 !
55    GCLEAR
60    ! Variable definitions:
65    !  On_off(I) ... State of unit I 0=off, 1=on
70    !  Unit$ ... Label for softkey
75    !  Strain_1(), Strain_2() ... Readings from units 1 & 2
80    !  Tyme_1(), Tyme_2() ... Time of readings
85    !  T_0() ... Start time from system
90    !  T_e() ... Elapsed time
95    !  T_i() ... Clock time
100   !  Rdg() ... Counter for readings
105   PRINT X_t$,X_d$
110   GOTO Main_menu
115 Set_up:  !
120   Rdg(1)=0
125   Rdg(2)=0
130   GCLEAR
135   GINIT
140   INPUT "Specify max time (seconds) for test 1",Max_time_1
145   Lvdt_cal_1=-.1!inches per volt
150   INPUT "Specify LVDT 1 calibration (default .1 in/V)",Lvdt_cal_1
155   Gage_1=.5
160   INPUT "Specify #1 spec. gage length, inches.(Default=.5)",Gage_1
165   INPUT "Specify max time (seconds) for test 2",Max_time_2
170   Lvdt_cal_2=-.1 !inches per volt
175   INPUT "Specify LVDT 2 calibration (default .1 in/V)",Lvdt_cal_2
180   Gage_2=.5
185   INPUT "Specify #2 spec. gage length, inches.(Default=.5)",Gage_2
190   Max_time=0
195   IF Max_time_1>Max_time AND Max_time_1>Max_time_2 THEN
200     Max_time=Max_time_1
205   ELSE
210     Max_time=Max_time_2
215   END IF
220   Min_strain=0
225   INPUT "Specify min % strain desired (Default=0)",Min_strain
230   INPUT "Specify max % strain desired",Max_strain
235   R_strain=Max_strain-Min_strain
240   GRAPHICS ON
245   VIEWPORT 0,100,10,100
250   WINDOW -Max_time*.2,Max_time,Min_strain-.1*R_strain,Max_strain+.1*R_strain
255   CLIP 0,Max_time,Min_strain,Max_strain
260   AXES Max_time/10,R_strain/10,0,Min_strain
265   CLIP OFF
270   LORG 6
275   CSIZE 3
280   IF Max_time<=1000 THEN Step_time=10
285   IF Max_time>1000 THEN Step_time=5
290   FOR I=0 TO Max_time STEP Max_time/Step_time
295     MOVE I,Min_strain-.05*R_strain
300     LABEL USING "K";I
305   NEXT I
310   MOVE Max_time/2,Min_strain-.1*R_strain
315   LABEL USING "K";"Time, seconds"
320   LORG 8
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves

```
325   FOR I=Min_strain TO Max_strain STEP R_strain/10
330     MOVE -.01*Max_time,I
335     LABEL USING "K";I
340   NEXT I
345   MOVE -.09*Max_time,R_strain/2+Min_strain
350   LORG 5
355   DEG
360   LDIR 90
365   IF Strain_type=2 THEN LABEL USING "K";"% Strain"
370   IF Strain_type=1 THEN LABEL USING "K";"% True Strain"
375   LDIR 0
380   LORG 5
385   PRINTER IS 1
390   FOR I=1 TO 2
395     On_off(I)=0
400     Units$(I)=":"&VAL$(I)&"is OFF"
405     T_e(I)=1.E-99
410   NEXT I
415   Tyme_int_1=(Max_time_1/4999) !Sets up time
420   Tyme_int_2=(Max_time_2/4999) !intervals
425 Main_menu:  !
430   GOTO Keys_setup
435 Main_menu_1:  !
440   GOSUB Time_interval
445 Main_menu_idle:  GOTO Main_menu_1
450 Keys_setup:!
455   OFF KEY
460   ON KEY 0 LABEL Units$(1) GOTO Unit_1_on_off
465   ON KEY 1 LABEL "Print 1" GOTO Print_1
470   ON KEY 2 LABEL "Plot1" GOTO Dis_plot_1
475   ON KEY 3 LABEL "Sto/Rec1" GOTO Sto_rec_1
480   ON KEY 4 LABEL "New Test" GOTO Set_up
485   ON KEY 5 LABEL Units$(2) GOTO Unit_2_on_off
490   ON KEY 6 LABEL "Print 2" GOTO Print_2
495   ON KEY 7 LABEL "Plot2" GOTO Dis_plot_2
500   ON KEY 8 LABEL "Sto/Rec2" GOTO Sto_rec_2
505   ON KEY 9 LABEL "QUIT" GOTO Quitter
510 Key_setup_1:  !
515   GOTO Main_menu_1
520 Unit_1_on_off:  !Select unit 1 for change
525   I=1
530   GOTO Units_on_off
535 Unit_2_on_off:  !Select unit 2 for change
540   I=2
545 Units_on_off:!Turn unit(I) on/off
550   IF On_off(I)=0 THEN
555     On_off(I)=1
556 !   T_0(I)=TIMEDATE
565     !
570     !
575     ! NOTE: 10 volts = 1 inch movement
580     !
585     !
590     IF I=1 THEN
595     PRINT "Set LVDT unit one to 0 and press return"
600     BEEP 200,.1
605     INPUT Which$
610     OUTPUT 709;"VRSAI1"
611     T_0(I)=TIMEDATE
615     ENTER 709;Lvdt1
620     ELSE
625     PRINT "Set LVDT unit two to 0 and press return"
630     BEEP 200,.1
635     INPUT Which$
640     OUTPUT 709;"VRSAI2"
641     T_0(I)=TIMEDATE
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
645     ENTER 709;Lvdt2
650     END IF
655     Unit$(I)="#"&VAL$(I)&"is ON"
660   ELSE
665     On_off(I)=0
670     Unit$(I)= #"&VAL$(I)&"is OFF"
675   END IF
680   GOTO Keys_setup
685 Print_1:  !Print data from unit 1
690   I=1
695   GOTO Print_data
700 Print_2:  !Print data from unit 2
705   I=2
710 Print_data:  !Hardcopy of data points
715   PRINTER IS 706
720   PRINT
725   PRINT
730   PRINT "Unit # ";I;"  ";TIMEDATE
735   PRINT "    #     Strain, %     Time, minutes      #     Strain, %     Ti
me, minutes"
740   FOR J=1 TO Nr_pts-1 STEP 2
745     PRINT USING Fmt1;J;Strain(I,J);Tyme(I,J);J+1;Strain(I,J+1);Tyme(I,J+1)
750   NEXT J
755 Fmt1:  IMAGE 2(5D,5X,D.DDDESZZ,5X,D.DDDESZZ,7X)
760   GOTO Keys_setup
765 Dis_plot_1:  !
770   I=1
775 Dis_plot_3:  !
780   GOSUB Which_plotr
785   GOSUB Plot_on
790   GOTO Main_menu
795 Dis_plot_2:  !
800   I=2
805   GOTO Dis_plot_3
810 Which_plotr:  !
815   FOR Q=0 TO 4
820     ON KEY Q LABEL "CRT" GOTO Plotr_crt
825     ON KEY Q+5 LABEL "Plotter" GOTO Plotr_plotr
830   NEXT Q
835 Wh_plotr_spin:  GOTO Wh_plotr_spin
840 Plotr_crt:  !
845   IF I=1 THEN Plotr_1$="CRT"
850   IF I=2 THEN Plotr_2$="CRT"
855   RETURN
860 Plotr_plotr:  !
865   IF I=1 THEN Plotr_1$="Plotter"
870   IF I=2 THEN Plotr_2$="Plotter"
875   RETURN
880 Plot_on:   !
885 Which_strain:  !
890   INPUT "1=True strain or 2=engineering strain?",Strain_type
895   IF Strain_type<1 OR Strain_type>2 THEN Which_strain
900   Min_strain=0
905   INPUT "Specify minimum strain desired (Default=0)",Min_strain
910   INPUT "Specify maximum strain desired",Max_strain
915   Min_time=0
920   INPUT "Specify minimum time desired (Default=0)",Min_time
925   INPUT "Specify maximum time desired",Max_time
930   PRINT "Strain axis:";Min_strain;"-";Max_strain
935   PRINT "Time axis:";Min_time;"-";Max_time
940   PRINT "Is this OK?"
945   GOSUB Yes_no
950   IF Answer$="N" THEN Plot_on
955   GCLEAR
960   GRAPHICS ON
965   GOSUB Which_plotr
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
970  IF (Plotr_1$="CRT" AND I=1) OR (Plotr_2$="CRT" AND I=2) THEN
975    ALPHA OFF
980    PLOTTER IS 3,"INTERNAL"
985  ELSE
990    PLOTTER IS 705,"HPGL"
995  END IF
1000 IF (Plotr_1$="CRT" AND I=1) OR (Plotr_2$="CRT" AND I=2) THEN
1005   VIEWPORT 0,125,20,90
1010 ELSE
1015   VIEWPORT 0,125,12,95
1020 END IF
1025 R_time=Max_time-Min_time
1030 R_strain=Max_strain-Min_strain
1035 WINDOW Min_time-.1*R_time,Max_time,Min_strain*.1*R_strain,Max_strain
1040 CLIP Min_time,Max_time,Min_strain,Max_strain
1045 AXES R_time/10,R_strain/10,Min_time,Min_strain
1050 CLIP OFF
1055 CSIZE 3
1060 IF Max_time<=1000 THEN Step_time=10
1065 IF Max_time>1000 THEN Step_time=5
1070 LORG 6
1075 FOR J=Min_time TO Max_time STEP R_time/Step_time
1080   MOVE J,Min_strain-.015*R_strain
1085   LABEL USING "K";J
1090 NEXT J
1095 MOVE Min_time+.5*R_time,Min_strain-.09*R_strain
1100 LABEL USING "K";"Time, seconds"
1105 LORG 8
1110 DEG
1115 FOR J=Min_strain TO Max_strain STEP R_strain/10
1120   MOVE Min_time-.03*R_time,J
1125   LABEL USING "K";J
1130 NEXT J
1135 LDIR 90
1140 LORG 5
1145 MOVE Min_time-.09*R_time,Min_strain+.5*R_strain
1150 IF Strain_type=2 THEN
1155 LABEL USING "K";"% Strain"
1160 ELSE
1165 LABEL USING "K";"True Strain"
1170 END IF
1175 LDIR 0
1180 Iplot=0
1185 OFF KEY
1190 CLIP Min_time,Max_time,Min_strain,Max_strain
1195 FOR J=1 TO 5000
1200   IF J<>1 THEN Ol_tyme=Tyme_x
1205   Strayn=0
1210   Tyme_x=0
1215   IF I=1 THEN
1220     Strayn=Strain_1(J)
1225     Tyme_x=Tyme_1(J)
1230   ELSE
1235     Strayn=Strain_2(J)
1240     Tyme_x=Tyme_2(J)
1245   END IF
1250   ON ERROR GOTO 1260
1255   IF Strain_type=1 THEN Strayn=LOG(1+(Strayn/100))
1260   OFF ERROR
1265   IF Tyme_x<Min_time THEN Plot_next
1270   IF Tyme_x>Max_time THEN
1275     J=5000
1280     GOTO Plot_next
1285   END IF
1290   Iplot=Iplot+1
1295   IF Iplot=1 THEN MOVE Tyme_x,Strayn
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
1300    IF Iplot<>1 AND (Tyme_x=0 AND Strayn=0) OR Ol_tyme>Tyme_x THEN Plot_next
1305    IF J<>1 AND Strayn=0 AND Tyme_x=0 THEN Plot_next
1310    DRAW Tyme_x,Strayn
1315 Plot_next: NEXT J
1320    IF Plotr_1$="CRT" OR Plotr_2$="CRT" THEN
1325      PENUP
1330    ELSE
1335      PEN 0
1340    END IF
1345  RETURN
1350 Yes_no: !
1355  FOR O=0 TO 4
1360    ON KEY O LABEL "Yes" GOTO Yess
1365    ON KEY O+5 LABEL "No" GOTO Noo
1370  NEXT O
1375 Yes_no_idle: GOTO Yes_no_idle
1380 Yess: !
1385  Answer$="Y"
1390  GOTO Yes_no_ret
1395 Noo: !
1400  Answer$="N"
1405 Yes_no_ret: !
1410  OFF KEY
1415  RETURN
1420 Sto_rec_1:!
1425  I=1
1430  GOTO Store_recall
1435 Sto_rec_2:!
1440  I=2
1445  GOTO Store_recall
1450 Store_recall:!
1455  OFF KEY
1460  FOR Q=0 TO 4
1465    ON KEY Q LABEL "SaveData" GOTO Store_1
1470    ON KEY Q+5 LABEL "Rec.Data" GOTO Recall_1
1475  NEXT Q
1480 Store_recall_1: GOTO Store_recall_1
1485 Store_1:! Stores data
1490  INPUT "File name for data storage",F_name$
1495  GOSUB Which_disk
1500  ON ERROR GOTO Store_error
1505 Store_2: !
1510  CREATE BDAT F_name$&"_X",1,40000
1515  CREATE BDAT F_name$&"_Y",1,40000
1520  CREATE BDAT F_name$&"_Z",1,4000
1525 Store_2_y: !
1530  OFF ERROR
1535  Err_eof=1
1540  ON ERROR GOTO Eof_error
1545  ASSIGN @File_x TO F_name$&"_X"
1550  IF I=1 THEN OUTPUT @File_x;Tyme_1(*)
1555  IF I=2 THEN OUTPUT @File_x;Tyme_2(*)
1560 Err_eof_1: !
1565  ASSIGN @File_x TO *
1570  Err_eof=2
1575  ASSIGN @File_y TO F_name$&"_Y"
1580  IF I=1 THEN OUTPUT @File_y;Strain_1(*)
1585  IF I=2 THEN OUTPUT @File_y;Strain_2(*)
1590 Err_eof_2: !
1595  ASSIGN @File_y TO *
1600  Err_eof=3
1605  ASSIGN @File_z TO F_name$&"_Z"
1610  OUTPUT @File_z;I,T_0(*),T_e(*),T_i(*),Rdg(*),Max_time_1,Max_time_2
1615 Err_eof_3: !
1620  ASSIGN @File_z TO *
1625  OFF ERROR
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
1630  GOTO Main_menu
1635 Eof_error: !
1640  OFF ERROR
1645  ON ERROR GOTO Eof_error
1650  IF Err_eof=1 THEN Err_eof_1
1655  IF Err_eof=2 THEN Err_eof_2
1660  IF Err_eof=3 THEN Err_eof_3
1665  GOTO Main_menu
1670 Which_disk:!
1675  OFF KEY
1680  FOR Q=0 TO 9
1685    ON KEY Q LABEL "" GOTO Which_disk_spin
1690  NEXT Q
1695  ON KEY 0 LABEL "82901-0" GOTO Drive_0
1700  ON KEY 1 LABEL "82901-1" GOTO Drive_1
1705  ON KEY 9 LABEL "INTERNAL" GOTO Drive_i
1710 Which_disk_spin: GOTO Which_disk_spin
1715 Drive_0: !
1720  MASS STORAGE IS ":HP82901,700"
1725  RETURN
1730 Drive_1: !
1735  MASS STORAGE IS ":HP82901,700,1"
1740  RETURN
1745 Drive_i: !
1750  MASS STORAGE IS ":INTERNAL"
1755  RETURN
1760 Store_error:!
1765  IF ERRN=54 THEN
1770    PRINT "Duplicate file name. Shall I overwrite?"
1775    GOSUB Yes_no
1780    OFF ERROR
1785    IF Answer$="Y" THEN Store_2_y
1790  END IF
1795  IF ERRN=64 THEN
1800    PRINT "Disk is full. Change disk or mass storage unit."
1805    BEEP 200,.5
1810    OFF ERROR
1815    GOTO Store_1
1820  END IF
1825  IF ERRN=80 THEN
1830    PRINT "Shut the bloomin' disk drive. It's cold out there!"
1835    OFF ERROR
1840    GOTO Store_1
1845  END IF
1850  IF ERRN=85 THEN
1855    INITIALIZE ":"&Msus$
1860    OFF ERROR
1865    GOTO Store_2
1870  END IF
1875  IF ERRN=90 THEN
1880    PRINT "Mass storage system error. Select another disk drive."
1885    OFF ERROR
1890    GOTO Store_1
1895  END IF
1900  PRINT "Error: ";ERRN
1905  OFF ERROR
1910  GOTO Main_menu
1915 Recall_1: !
1920  INPUT "File name to be recalled (omit suffixes)",F_name$
1925  PRINT "Which disk drive?"
1930  GOSUB Which_disk
1935  ASSIGN @File_x TO F_name$&"_x"
1940  ON ERROR GOTO 1955
1945  IF I=1 THEN ENTER @File_x;Tyme_1(*)
1950  IF I=2 THEN ENTER @File_x;Tyme_2(*)
1955  ASSIGN @File_x TO *
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
1960  OFF ERROR
1965  ON ERROR GOTO 1985
1970  ASSIGN @File_y TO F_name$&"_Y"
1975  IF I=1 THEN ENTER @File_y;Strain_1(*)
1980  IF I=2 THEN ENTER @File_y;Strain_2(*)
1985  ASSIGN @File_y TO *
1990  OFF ERROR
1995  ON ERROR GOTO 2010
2000  ASSIGN @File_z TO F_name$&"_Z"
2005  ENTER @File_z;I,T_0(*),T_e(*),T_i(*),Rdg(*),Max_time_1,Max_time_2
2010  ASSIGN @File_z TO *
2015  OFF ERROR
2016  Factor=1
2018  INPUT "Specify multiplication factor for data. Def=1",Factor
2019  IF Factor=1 THEN
2020    GOSUB Plot_on
2021  ELSE
2022    FOR J=1 TO 5000
2023      IF I=1 THEN Strain_1(J)=Strain_1(J)*Factor
2024      IF I=2 THEN Strain_2(J)=Strain_2(J)*Factor
2025    NEXT J
2027  GOSUB Plot_on
2028  END IF
2030 Quitter: !
2031  BEEP 2000,.1
2035  FOR Q=0 TO 4
2040    ON KEY Q LABEL "QUIT" GOTO Quitter_1
2045    ON KEY Q+5 LABEL "Continue" GOTO Keys_setup
2050  NEXT Q
2055 Quitter_idle: GOTO Quitter_idle
2060 Quitter_1: STOP
2065 Time_interval: !
2070  IF On_off(1)=0 THEN Time_int_1
2075  T_e(1)=TIMEDATE-T_0(1)
2080  IF T_e(1)>=Rdg(1)*Tyme_int_1 THEN GOSUB Read_1
2085 Time_int_1: !
2090  IF On_off(2)=0 THEN RETURN
2095  T_e(2)=TIMEDATE-T_0(2)
2100  IF T_e(2)>=Rdg(2)*Tyme_int_2 THEN GOSUB Read_2
2105  RETURN
2110 Read_1: !
2115  Rdg(1)=Rdg(1)+1
2120  IF Rdg(1)>5000 THEN
2125    Rdg(1)=5000
2130    RETURN
2135  END IF
2140  IF Rdg(1)=1 THEN
2145    GOSUB Display_1_on
2150  END IF
2155  IF T_e(1)>Max_time_1 THEN
2160    On_off(1)=0
2165    ON KEY 0 LABEL "#1 DONE" GOTO Unit_1_on_off
2170  END IF
2175    OUTPUT 709;"VRSAI1"
2180    ENTER 709;Strain_1(Rdg(1))
2185    Strain_1(Rdg(1))=100*Lvdt_cal_1*(Strain_1(Rdg(1))-Lvdt1)/Gage_1
2190    Tyme_1(Rdg(1))=T_e(1)
2195    LORG 5
2200    CSIZE 2
2205    IF Strain_type=2 THEN
2210    MOVE Tyme_1(Rdg(1)),Strain_1(Rdg(1))
2215    ELSE
2220    ON ERROR GOTO 2230
2225    MOVE Tyme_1(Rdg(1)),LOG(Strain_1(Rdg(1))+1)
2230    OFF ERROR
2235    END IF
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
2240    LABEL USING "K";"1"
2245  RETURN
2250 Read_2: '
2255  Rdg(2)=Rdg(2)+1
2260  IF Rdg(2)>5000 THEN
2265    Rdg(2)=5000
2270    RETURN
2275  END IF
2280  IF Rdg(2)=1 THEN
2285    GOSUB Display_2_on
2290  END IF
2295  IF T_e(2)>Max_time_2 THEN
2300    On_off(2)=0
2305    ON KEY 5 LABEL "#2 DONE" GOTO Unit_2_on_off
2310  END IF
2315    OUTPUT 709;"VR5AI2"
2320    ENTER 709;Strain_2(Rdg(2))
2325    Strain_2(Rdg(2))=100*Lvdt_cal_2*(Strain_2(Rdg(2))-Lvdt2)/Gage_2
2330    Tyme_2(Rdg(2))=T_e(2)
2335    LORG 5
2340    CSIZE 2
2345    IF Strain_type=2 THEN
2350    MOVE Tyme_2(Rdg(2)),Strain_2(Rdg(2))
2355    ELSE
2360    ON ERROR GOTO 2370
2365    MOVE Tyme_2(Rdg(2)),LOG(Strain_2(Rdg(2))+1)
2370    OFF ERROR
2375    END IF
2380    LABEL USING "K";"2"
2385  RETURN
2390 Display_1_on: '
2395  Disp_1=1
2400  BEEP 2000,.1
2405  RETURN
2410 Display_2_on: '
2415  Disp_2=1
2420  RETURN
2425  END
```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```
10    ! PROGRAM TO COMPUTE STRAIN RATES GIVEN THE DATA DISC FROM A TEMPERATURE C
YCLING TEST.
30    ! IT IS USER FRIENDLY AND MENU-DRIVEN.
40    !WRITTEN 10-19-89 BY LT EARL F. GOODSON,SR.
50    !EDITED  10-21-89 BY LT EARL F. GOODSON,SR.
60    DIM Strain_1(5000),Tyme_1(5000),True_strain(5000),Str_rate(1000),A_str(100
0)
71    DIM Log_rate(2000)
80    Nr_pnts=5000
81    PRINTER IS 1
90    I=1
100   PRINT "PROGRAM TO CALC STRAIN RATES GIVEN THE DATA DISC FROM A TEMPERATURE
 CYCLING TEST."
110   PRINT " HIT CONTINUE TO BEGIN"
111   PAUSE
113   GOTO Keys_setup
114 Disc:  !
115   OFF ERROR
120   PRINT "PLACE DATA DISC IN THE INTERNAL DRIVE."
130   INPUT "FILENAME TO BE RECALLED(OMIT SUFFIXES)",F_name$
131   ON ERROR GOTO Disc
140   MASS STORAGE IS ":INTERNAL" ! RECOVERS TIME
150   !                              DATA ARRAY
160   !
170   ASSIGN @File_x TO F_name$&"_X"
180   ON ERROR GOTO 200
190   ENTER @File_x;Tyme_1(*)
200   ASSIGN @File_x TO *
210   OFF ERROR
220   ON ERROR GOTO 270
230   ASSIGN @File_y TO F_name$&"_Y"! RECOVERS ENG
240   !                             STRAIN DATA ARRAY
250   !
260   ENTER @File_y;Strain_1(*)
270   ASSIGN @File_y TO *
280   OFF ERROR
351   GOTO See_all
360   !
370   !ASSIGNS TRUE STRAIN VALUES AN ARRAY NUM.
380   !
381 See_all:  !
383   Q=0
384   PRINT "PLEASE WAIT UNTIL THIS MESSAGE DISAPPEARS.  THE TRUE STRAIN ARRAY I
S BEING FILLED"
390   FOR J=1 TO 4999 STEP 1 ! FILLS TRUE STRAIN ARRAY
391   Q=Q+1
400     True_strain(Q)=LOG(1+(Strain_1(J)/100))
401     IF True_strain(Q)=0 THEN GOTO 421
410   NEXT J
421   OUTPUT 2;"K";
422   GOTO Keys_setup
430   !
440   !
450   !SOFT KEY SET-UP FOR MAIN MENU
460   !
470   !
480 Keys_setup:  !
481   OUTPUT 2;"K"; !  CLEAR SCREEN CMD
490   OFF KEY
500   ON KEY 0 LABEL "PRN E,T" GOTO Print_1
510   ON KEY 1 LABEL "PL/PR ER" GOTO Strain_rate_1
520  !ON KEY 2 LABEL "CALC DIF" GOTO DIFF_COMP
530   ON KEY 3 LABEL "DSUBC" GOTO Act_ener
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables

```
540   ON KEY 4 LABEL "QUIT" GOTO Quitter
541   ON KEY 5 LABEL "NEWTEST" GOTO Disc
550 Key_idle:   GOTO Key_idle
560   !
570   ! SUBPROCEDURE TO PRINT ALL STRAINS AND TIME
580   ! ON THE PRINTER
590   !
600   !
610 Print_1:  !
620  !PRINT "PRINT_1 ENTERED"!   PRINTS TRUE STRAINS AND TIMES
626   Strtl=2
627   Stpl=4999
628   Intvl=2
631   INPUT "INPUT RDG TO START AT,(DEFAULT = 1ST RDG)",Strtl
632   INPUT "RDG TO STOP ON,(DEFAULT = 4999)",Stpl
633   INPUT "INPUT INTERVAL TO CALC TRUE STRAINS,(DEF=2 RDGS)",Intvl
634   PRINTER IS 706
635   PRINT "FILENAME IS ";F_name$
637   PRINT "  RDG #   TRUESTRAIN     TIME,SEC           RDG #   TRUESTRAIN
TIME,SEC"
639   FOR J=Strtl TO Stpl STEP Intvl*2
640     PRINT USING Fmtl;J;True_strain(J);Tyme_1(J);J+Intvl;True_strain(J+Intvl)
;Tyme_1(J+Intvl)
641     ON ERROR GOTO 644
642   NEXT J
643 Fmtl:   IMAGE 2(5D,5X,SD.DDDESZZ,5X,SD.DDDESZZ,7X)
644   PRINTER IS 1
645   OFF ERROR
646   GOTO Keys_setup
647   !
650   !
660   !SUBPROCEDURE TO PRINT AN INTERVAL OF ALL
670   !STRAIN RATES AND STRAINS WITH PLOTTING
680   !
690   !
700 Strain_rate_1:  !
701   PRINTER IS 1
702   Interv=10
704   Strt=2
705   Stp=1900
706   Ans_1$="N"
707   Prt=1
708   Ans$="Y"
709   Tr=0
712   INPUT "INPUT INTERVAL BETWEEN STRAIN RATES,(DEF=10 RDGS)",Interv
713   I=Interv
715   INPUT "INPUT VALUE TO START AT,(DEFAULT=1ST RDG)",Strt
720   INPUT "INPUT VALUE TO STOP AT,(DEFAULT=1900 RDG)",Stp
721   INPUT "DO YOU WANT A HARD COPY OF DATA?,(DEFAULT=NO)",Ans_1$
722   IF Ans_1$="Y" THEN
725   INPUT "HIT ENTER FOR CRT OR 2 FOR EXT PRINTER,(DEF=CRT)",Prt
726   END IF
729   PRINT "ARE YOU SURE YOU WANT TO START AT ";Strt;" , STOP AT ";Stp;" OVER I
NTERVAL OF ";Interv
730   INPUT "INPUT Y/N,(DEFAULT=YES)",Ans$
731   IF Ans$="N" THEN
732     GOTO Strain_rate_1
733     OUTPUT 2;"K";
734   ELSE
735     PRINT "PLEASE WAIT FOR MENU TO APPEAR.  STRAIN RATE ARRAY IS BEING FILLE
D."
736   END IF
737   IF Prt=2 THEN PRINTER IS 706
738     IF Ans_1$="Y" THEN
740       PRINT "FILENAME IS ";F_name$
741       PRINT " INTERVAL     AVG STRAIN     STRAIN RATE"!  INTERVAL     AVG ST
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```
RAIN     STRAIN R"
742      END IF
750    FOR J=Strt TO Stp STEP Interv
751      Tr=Tr+1
760      Str_rate(Tr)=ABS(((True_strain(J+Interv)-True_strain(J))/(Tyme_1(J+Inter
v)-Tyme_1(J))))
761     !Log_rate(Tr)=LGT(ABS(Str_rate(Tr)))
770      A_str(Tr)=(True_strain(J+Interv)+True_strain(J))/2
780      ON ERROR GOTO 830
800      IF Ans_1$="Y" THEN
801      PRINT USING Fmt2;J;"-";J+I;A_str(Tr);Str_rate(Tr)!;J+I;"-";J+2*I,A_str(1
+Tr);Str_rate(1+Tr)
804      END IF
810      NEXT J
820 Fmt2:    IMAGE (4D,K,4D,5X,SD.DDDESZZ,5X,SD.DDDESZZ,3X)
830      OFF ERROR
840      PRINTER IS 1
850      OFF KEY
851    ! OUTPUT 2;"K";
860      ON KEY 1 LABEL "PLOT ER,E" GOTO Plot_er
861      ON KEY 2 LABEL "NEWTEST" GOTO Disc
862      ON KEY 3 LABEL "MENU" GOTO Keys_setup
863      ON KEY 4 LABEL "SLOPE" GOTO Sloper
870 Plot_idle:     GOTO Plot_idle
880      GOTO Keys_setup
890      !
900      !
910      !SUB TO PLOT STRAIN RATE VS STRAIN
920 Plot_er:    !
921      OFF KEY
922      Ans4$="N"
924      Ylog=0     ! TELLS PLOT TO USE REG Y-AXIS
925      PRINT "THIS SECTION GIVES YOU SEVERAL CHOICES OF PLOTS.  YOU MAY NEED IT
ERATION TO GET THE"
926      PRINT "SCALE AND THE LIMITS RIGHT.  DEFAULT IS A SEMI-LOG PLOT.  YOU ALS
O CAN PLOT REGULAR"
927      PRINT "AXES.  AUTO SCALING REQUIRES SOME PATIENCE SINCE IT USES YMAX AND
 YMIN, SO TRY AGAIN"
928      PRINT
932      X1$="TRUE STRAIN,IN/IN"
940      Y1$="LOG STRAIN RATE"
950      T$="TEMP CYCLING EXP"
951      INPUT "PLOT LOG STRAIN RATE WITH REG AXES?,(DEF=NO)",Ans4$
953      IF Ans4$="N" THEN
954        Ylog=1
955        Y1$="STRAIN RATE,SEC-1"
956        X1$="TRUE STRAIN,IN/IN"
958        INPUT "PLOT SEMI-LOG W/Y AS LOG AXIS?,(YES=DEF,NO=0)",Ylog
961      END IF
962      Ans2=1
963      INPUT "INPUT TITLE OF PLOT(DEF=TEMP CYCL EXP)",T$
965     INPUT "1 FOR CRT OR 2 FOR EXT PLOT,(DEF=CRT)",Ans2
966     IF Ans2=2 THEN
967       PLOTTER IS 705,"HPGL"
968     ELSE
969       GCLEAR
970       ALPHA OFF
971       GRAPHICS ON
972     END IF
973     IF Ans4$="Y" THEN
974       CALL Auscl(Log_rate(1),Log_rate(Tr),0,Mn_r,Mx_r,Tc_r)
975     ELSE
976       CALL Auscl(Str_rate(1),Str_rate(Tr),0,Mn_r,Mx_r,Tc_r)
977     END IF
980      CALL Auscl(A_str(1),A_str(Tr),0,Mn_e,Mx_e,Tc_e)
984      IF Ans4$="Y" THEN
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```
990      CALL Plot(Mn_e,Mx_e,Mn_r,Mx_r,Tc_e,Tc_r,0,Ylog,X1$,Y1$,A_str(*),Log_ra
te(*),Tr,T$)
991      ELSE
992      CALL Plot(Mn_e,Mx_e,Mn_r,Mx_r,Tc_e,Tc_r,0,Ylog,X1$,Y1$,A_str(*),Str_ra
te(*),Tr,T$)
993     END IF
995     PRINTER IS 1
996     PRINT "HIT CONTINUE TO RESUME THE PROGRAM"
997       PAUSE
998       GINIT
999       GCLEAR
1000      GRAPHICS OFF
1001      ALPHA ON
1002    GOTO Keys_setup
1010    !
1020    ! SUB TO PRINT DESIGNATED STRAIN RATES
1030    !
1040 Act_ener:  !
1050    PRINT "ACT_ENER ENTERED"
1051    Ans7$="Y"
1052    INPUT "INPUT TEMP 1",T1
1053    INPUT "INPUT STRAIN RATE 1",S1
1054    INPUT "INPUT TEMP 2",T2
1055    INPUT "INPUT STRAIN RATE 2",S2
1056    Qsubc=(2.303*1.98)*(LGT(S1)-LGT(S2))/((1/(T1+273))-(1/(T2+273)))
1057    PRINT "ACTIVATION ENERGY = ";Qsubc
1058    INPUT "DO YOU WANT TO GO AGAIN(DEF=YES)",Ans7$
1059    IF Ans7$="Y" THEN GOTO Act_ener
1061    GOTO Keys_setup
1070    !
1080    ! SUB TO PRINT DESIGNATED STRAINS
1090 Sloper:  !
1100    PRINT "SLOPER ENTERED"
1110    GOTO Keys_setup
1120    !
1130    ! SUB TO QUIT STRAIN RATE PROGRAM
1140 Quitter:  !
1150    BEEP 2000,.1
1160    FOR Q=0 TO 4
1170      ON KEY Q LABEL "QUIT" GOTO Quitter_1
1180      ON KEY Q+5 LABEL "CONTINUE" GOTO Keys_setup
1190    NEXT Q
1200 Quitter_idle:      GOTO Quitter_idle
1210 Quitter_1:    STOP
1220    END
1221    !
1222    !
1230  SUB Ausc1(Min,Max,Offset,Minm,Maxm,Tick)       ! S825            12/02/81
1240 !PRINT "AUTO-SCALE ENTERED"
1241  !
1250  INTEGER Power,N,Dir
1290  Range=ABS(Max-Min)
1300  Power=INT(LGT(Range))
1310  Norm=Range/10^Power
1320  N=10*(Norm>=5)+5*((Norm<5) AND (Norm>=2))+2*((Norm<2) AND (Norm>1))+(Norm<
=1)
1330  Inter=DROUND(N*10^(Power-1),1)
1340  Dir=SGN(Min-Max)
1350  X=(Min-Offset)/10^Power
1360  GOSUB Rout
1370  Minm=Rout*10^Power+Offset
1380  Dir=SGN(Max-Min)
1390  X=(Max-Offset)/10^Power
1400  GOSUB Rout
1410  Maxm=Rout*10^Power+Offset
1420  Tick=DROUND(ABS(Maxm-Minm)/Inter+1,INT(LGT(ABS((Maxm-Minm)/Inter+1))+1))
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```
1430  GOTO Exit
1440 Rout: Test=ABS(X)-INT(ABS(X))  ! ROUND X TO MULTIPLE OF N IN DIRECTION Dir.
1450  Digit=INT(10*Test)
1460  Delta=Digit*(N=10)+Digit MOD N*(N<>10)
1470  Round=((SGN(X)*Dir>0)*N-SGN(X)*Dir*Delta)/10*((Test-Digit/10 OR Delta)<>0
1480  IF ABS(SGN(X)*Digit/10+Dir*Round)>1 THEN Round=1-Digit/10
1490  Rout=SGN(X)*(INT(ABS(X))+Digit/10)+Dir*Round
1500  RETURN
1550 Exit: SUBEND
1560       !
1570       !
2270  SUB Plot(Xmin,Xmax,Ymin,Ymax,Xtic,Ytic,Xlog,Ylog,X$,Y$,X(*),Y(*),N,Title$
2280                                                    !  3825          01/26/82
2290                                                   !PRINT "PLOTTER ENTERED"
2291                                                   !
2300  INTEGER Pointr,Minor,Majtic,Mintic,Penc
2310  DEG
2320  N1=INT(ABS(N))
2530  Xmajor=INT(ABS(Xtic))                                      ! VARIABLE SETUP
2540  Ymajor=INT(ABS(Ytic))
2550  Cxmax=Xmax
2560  IF Xlog THEN Cxmax=LGT(Xmax)
2570  Cxmin=Xmin
2580  IF Xlog THEN Cxmin=LGT(Xmin)
2590  Cymax=Ymax
2591  Y1=(1.E-8+Ymax)
2600  IF Ylog THEN Cymax=LGT(Y1)
2610  Cymin=Ymin
2611  Y2=(1.E-8+Ymin)
2620  IF Ylog THEN Cymin=LGT(Y2)
2630  IF Cxmin<Cxmax THEN GOTO X_ok                        ! MAKE SURE Max > Min
2640  Dummy=Cxmin
2650  Cxmin=Cxmax
2660  Cxmax=Dummy
2670 X_ok:  IF Cymin<Cymax THEN GOTO Y_ok
2680  Dummy=Cymin
2690  Cymin=Cymax
2700  Cymax=Dummy
2710 Y_ok:Cheight=15/4.54              ! CHARACTER SIZE AND TICK LENGTH IN GDU
2720  Cwidth=.6*Cheight
2730  Tick=Cwidth
2740  IF RATIO>=1 THEN                   !CALC VERT. AND HORIZ. LIMITS IN GDU
2750     Vert=100
2760     Horiz=RATIO*100
2770  ELSE
2780     Horiz=100
2790     Vert=100/RATIO
2800  END IF
2810  Gdux=Horiz-10*Cwidth-Cheight-Tick                      ! AXIS LENGTH IN GDU
2820  Gduy=Vert-3.5*Cwidth-2.5*Cheight-Tick
2830           ! CONVERT HARD LIMITS 0,Horiz TO DATA UNITS Xlower, Xupper, etc.
2840  Xlower=Cxmin-(9.5*Cwidth+Cheight+Tick)/Gdux*(Cxmax-Cxmin)
2850  Xupper=Cxmax+.5*Cwidth/Gdux*(Cxmax-Cxmin)
2860  Ylower=Cymin-(Cheight+9.5*Cwidth+Tick)/Gduy*(Cymax-Cymin)
2870  Yupper=Cymax+1.5*Cheight/Gduy*(Cymax-Cymin)
2880  Xticlen=Tick/Gduy*(Cymax-Cymin)
2890  Yticlen=Tick/Gdux*(Cxmax-Cxmin)
2900  VIEWPORT 0,Horiz,0,Vert                          ! SETUP PLOTTING PARAMETERS.
2910  PIVOT 0
2920  MOVE 0,0
2930  WINDOW Xlower,Xupper,Ylower,Yupper
2940  CSIZE Cheight,Cwidth/Cheight
2950  CLIP Cxmin,Cxmax,Cymin,Cymax
2960  IF Xmajor=0 THEN GOTO Y_axis
2970  Minor=INT(10*(ABS(Xtic)-Xmajor))                             !PLOT X AXIS
2980  Tickspace=Cxmax-Cxmin
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```
2990  IF Xmajor>1 THEN Tickspace=(Cxmax-Cxmin)/(Xmajor-1)
3000  MOVE Cxmin,Cymin
3010  DRAW Cxmax,Cymin
3020  LORG 8
3030  LDIR 0
3040  FOR Majtic=1 TO Xmajor
3050     Majpos=Cxmin+Tickspace*(Majtic-1)
3060     MOVE Majpos,Cymin-Xticlen
3070     Labl=Majpos
3080     IF Xlog THEN Labl=10^Majpos
3090     IF ((ABS(Labl)>=1.E+6) OR (ABS(Labl)<1.E-4)) AND (Labl<>0) THEN GOTO Fl
oatx
3100     IF Labl<>0 THEN
3110        Temp=-INT(LGT(ABS(Labl)))-1
3120        IF Temp<=0 THEN Temp=0
3130        Labl=DROUND(Labl,7-Temp)
3140     END IF
3150     CLIP OFF
3160     LABEL USING "#,K";Labl
3170     CLIP ON
3180     PENUP
3190     GOTO Xticmark
3200 Floatx:CLIP OFF
3210     Labl=DROUND(Labl,2)
3220     LABEL USING "#,K";Labl
3230     CLIP ON
3240     PENUP
3250 Xticmark:MOVE Majpos,Cymin
3260     IF Xtic>0 THEN IDRAW 0,Xticlen
3270     IF (Minor=0) OR (Majtic=Xmajor) THEN GOTO No_xminor
3280     Mininc=Tickspace/(Minor+1)                              ! PLOT MINOR TICKS
3290     IF Xlog THEN Mininc=(10^(Majpos+Tickspace)-10^Majpos)/(Minor+1)
3300     FOR Mintic=1 TO Minor
3310        Minpos=Majpos+Mininc*Mintic
3320        IF Xlog THEN Minpos=LGT(10^Majpos+Mininc*Mintic)
3330        MOVE Minpos,Cymin
3340        IDRAW 0,Xticlen/2
3350     NEXT Mintic
3360 No_xminor: NEXT Majtic
3370  LDIR 0                                                     ! X AXIS LABEL
3380  LORG 4
3390  MOVE (Xlower+Xupper)/2,Ylower
3400  CLIP OFF
3410  LABEL USING "#,K";X$
3420  CLIP ON
3430  PENUP
3440 Y_axis:   IF Ymajor=0 THEN GOTO Dataplot
3450  Minor=INT(10*(ABS(Ytic)-Ymajor))                           ! PLOT Y AXIS
3460  Tickspace=Cymax-Cymin
3470  IF Ymajor>1 THEN Tickspace=(Cymax-Cymin)/(Ymajor-1)
3480  MOVE Cxmin,Cymin
3490  DRAW Cxmin,Cymax
3500  LORG 8
3510  LDIR 0
3520  FOR Majtic=1 TO Ymajor
3530     Majpos=Cymin+Tickspace*(Majtic-1)
3540     MOVE Cxmin-Yticlen,Majpos
3550     Labl=Majpos
3560     IF Ylog THEN Labl=10^Majpos
3570     IF ((ABS(Labl))=1.E+6) OR (ABS(Labl)<1.E-4)) AND (Labl<>0) THEN GOTO Fl
oaty
3580     IF Labl<>0 THEN
3590        Temp=-INT(LGT(ABS(Labl)))-1
3600        IF Temp<=0 THEN Temp=0
3610        Labl=DROUND(Labl,7-Temp)
3620     END IF
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```
3630      CLIP OFF
3640      LABEL USING "#,K";Labl
3650      CLIP ON
3660      PENUP
3670      GOTO Yticmark
3680 Floaty:    CLIP OFF
3690      Labl=DROUND(Labl,2)
3700      LABEL USING "#,K";Labl
3710      CLIP ON
3720      PENUP
3730 Yticmark:   MOVE Cxmin,Majpos
3740      IF Ytic>0 THEN IDRAW Yticlen,0
3750      IF (Minor=0) OR (Majtic=Ymajor) THEN GOTO No_yminor
3760      Mininc=Tickspace/(Minor+1)                          ! PLOT MINOR TICKS
3770      IF Ylog THEN Mininc=(10^(Majpos+Tickspace)-10^Majpos)/(Minor+1)
3780      FOR Mintic=1 TO Minor
3790         Minpos=Majpos+Mininc*Mintic
3800         IF Ylog THEN Minpos=LGT(10^Majpos+Mininc*Mintic)
3810         MOVE Cxmin,Minpos
3820         IDRAW Yticlen/2,0
3830      NEXT Mintic
3840 No_yminor: NEXT Majtic
3850   LDIR 90                                                ! Y AXIS LABEL
3860   LORG 6
3870   MOVE Xlower,(Ylower+Yupper)/2
3880   CLIP OFF
3890   LABEL USING "#,K";Y$
3900   CLIP ON
3910   PENUP
3920 Dataplot:   LDIR 0
3930   IF N1=0 THEN GOTO Titleplot
3940   LORG 5                                                 !PLOT DATA
3950   Penc=-2
3960   FOR Pointr=1 TO N1
3970      Xx=X(Pointr)
3980      IF Xlog THEN Xx=LGT(X(Pointr))
3990      Yy=Y(Pointr)
4000      IF Ylog THEN Yy=LGT(Y(Pointr))
4010      IF Penc=-2 THEN MOVE Xx,Yy
4020      IF Penc=-1 THEN DRAW Xx,Yy
4030      IF N<0 THEN
4040         CLIP OFF
4050         LABEL USING "#,K";"*"
4060         CLIP ON
4070         PENUP
4080      END IF
4090      Penc=-1-(N<0)
4100   NEXT Pointr
4110 Titleplot:   LORG 5                                       ! PLOT TITLE
4120   MOVE (Xlower+Xupper)/2,Yupper
4130   CLIP OFF
4140   LABEL USING "#,K";Title$
4150   CLIP ON
4160   PENUP
4260   SUBEND
```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

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